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INVESTIGATION OF 3-D FABRICATION OF ABLATIVE MATERIALS

FINAL REPORT
8 September 1965 to 18 October 1966

AVSSD - 0308 -66 - RR

November 1966

Prepared Under
Contract No. NAS-9-5207

By

AVCO MISSILES, SPACE AND ELECTRONICS GROUP
SPACE SYSTEMS DIVISION
201 Lowell Street
Wilmington, Massachusetts 01887

For

PROPULSION AND POWER DIVISION
NASA MANNED SPACECRAFT CENTER
Houston, Texas 77058

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APPROVED

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FOREWORD

This report was prepared by Avco Corporation, Space Systems Division, Lowell, Massachusetts, under NASA, MSC contract Number NAS9-5207, dated 8 September 1965. The time period for the performance of this contract was 8 September 1965 to 18 October 1966. This report is of work performed by Avco SSD during the course of the contract. Program manager was Ardashes Nahabedian of the SSD Materials Development Department. The project engineer was Dr. Charles T. Hughes, who had overall technical control of the work. The mechanical testing was done by Dr. E. Lenoe and G. Wassil; the weaving of the Avco 3-D materials was handled by R. King; the sample molding and impregnation, by P. Roy and W. Holmes; and the loom design, by B. Stiff, S. Motta, and R. King. The technical monitor for the National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas, was Julian W. Jones of the Propulsion and Power Division.

ABSTRACT

This report presents an evaluation of the fabrication and properties of three dimensionally reinforced materials. The information presented in the report is organized into four areas. In the first, nine methods of state-of-the-art fabric production are compared on the basis of 1) ease of fabrication, 2) amount of machine modification necessary to make 8-inch-thick fabric, and 3) the maximum thickness capability based on present industry know how. The determination and comparison of thermal, physical, and mechanical properties of these fabrics as composites with epoxy resin constitutes the second area. Samples from only five of the techniques were available for this property determination. The third area is the fabrication of experimental thruster chambers from one of the best techniques, Avco 3-D. The fourth area is devoted to the development and discussion of preliminary designs for fabrication of monolithic, cylindrical coordinate, three dimensionally reinforced thrusters with integral metallic throats.

Billets 8-inches thick can be made from three of the fabric making techniques described. These are Avco 3-D, double-loop fabric laminates, and needled fabrics, in the order of decreasing interlaminar strength. Interlaminar tensile strengths of 40, 000 psi (15 times the strength of the reference laminate) have been obtained with Avco 3-D, while the double-loop and needled fabric laminates gave about twice the strength of the reference; torsional properties showed similar improvement, Thermal shock resistance of the three dimensionally reinforced material also showed substantial improvement over reference laminates, even at low Z direction reinforcement concentrations.

Three test chambers were made with Avco 3-D reinforcement in different thread geometries and chamber axis orientation.

Two loom designs are described for making monolithic, cylindrical coordinate, three dimensionally reinforced rocket motors with integral metallic throats. Both of these designs could be implemented with present knowledge and minimal time and machine development,

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I. INTRODUCTION AND SUMMARY

The objectives of this program are (1) to evaluate methods of making a three-dimensional (3-D) reinforcement having no planes of weakness, (2) to demonstrate the properties of composites made from these reinforcements, and (3) to select one or more methods for further effort.

The benefits to be obtained by such a construction are evident:

1) Greatly improved performance in applications now using normal fabric layup.

2) Usage in applications not now using reinforced plastics because of the present limitations of these materials.

3) Relaxation of the rigid, materials-and-process specifications now required to obtain high-quality, delamination-free moldings.

Reinforced plastics generally are made either from woven or nonwoven fabrics or from random fibers in a matrix of resins such as epoxy, phenolic, polyester, and others. The reinforcing fibers tend to lie in a plane, either by design, as in fabrics, or as a consequence of molding, which compresses random fibers into a layered structure. The result is a composite either with planes of weakness or a direction in which tensile strength is low compared to other directions.

There are many instances in which this low interlaminar strength would limit the usefulness of the composite or necessitate very rigid specifications on the raw materials and processes. Examples include (1) the cracking of rocket nozzles and thrust chambers, especially on multiple firings; (2) fracture of tips of reentry vehicles when subjected to asymmetric loadings; (3) spalling of heat shields or rocket nozzles (especially if workmanship is poor, if resin is not fully cured, or if the fabric angle is too nearly parallel to the surface); (4) interlaminar failure of composites subjected to compression loading parallel to the fabric; and (5) cracking of large phenolic moldings if the prepreg is not precisely correct, or if the cure cycle is not precise.

Nine methods are discussed in detail, both describing the fabrication as well as assessing the potential of the method for producing machined cylindrical billets 8 inches in diameter and 12 inches in length. Tensile, shear, thermal-expansion, and thermal-shock behavior of epoxy-impregnated samples representing eight of these methods are reported. Impregnation techniques, which are described in detail, were developed for proper molding of these materials with epoxy resins and phenolic-epoxy systems.

Three methods, Avco 3-D, double-loop fabric as laminates, and needling can produce the required billet sizes for nozzle fabrication without further large scale development. These methods have produced masked improvement in thermal shock resistance and interlaminar strength over conventional laminates. Test chambers were fabricated with three variations of Avco 3-D fabric for test firing as a start on a property-performance correlation. Further development of this correlation is recommended through study of the cloth manufacturing variables and fabric impregnation variables during the fabrication of more test chambers,

II. RESULTS AND DISCUSSION OF RESULTS

A. FABRIC CONSTRUCTION METHODS

Proper evaluation of textile processes as a means of reducing the planes of weakness in a laminated material required broad coverage of numerous textile fabrication techniques. Few techniques showed an initial capability for producing glass fabric of even an inch in thickness, let alone the required 8-inch maximum thicknesses. Techniques producing at least a 1-inch thickness included needling, double loop, sewing, and the new technique of fabric construction developed at Avco. Valid assessment, however, of the potential of any process for producing a fabric 8 inches thick by 12 inches long had to be based upon broad review of industry practice of many techniques. This review depended greatly upon numerous contacts in the field of textiles, including large-scale producers, small specialty organizations, textile equipment manufacturers, consultants, textile research institutions, and educators.

This investigation included contacts with the companies, institutions, and individuals listed in Table I. The varied composition of Table I shows that many discussions were made and more detailed information obtained from the broad range of company size and interest described above.

TABLE I

COMPANIES, INSTITUTIONS, AND PEOPLE CONTACTED

	Company	Response
1.	American Velvet Company, Stonington, Conn.	Make multiple warp fabric (2 ply) in glass; maximum machine capacity is 3/8-inch.
2.	Bigelow-Sanford, Thompsonville, Conn.	Carpet manufacturers; can weave two ply fabric with stuffer yarns, and with thick yarns might obtain 1/2-inch thickness; do not feel they can make double pile fabric in glass.
3.	Callawav Mills, Lagrange, Ga.	Makers of tufted fabrics such as toweling; initial confidence in making multiple warp fabric in glass not born out.
4.	Deering Milliken Research Corp., Spartanburg, S. C.	no response.
5.	Draper Bros., Canton, Mass.	Weave very wide fabrics and make very wide needled fabrics; in samples.

6.	Draper Corporation, Hopedale, Mass.	Loom manufacturer; no information available on multiple warp looms.
7.	Fabric Research, Jamaica Plain, Mass.	Research laboratory; could not supply samples in glass readily; did not pursue further.
8.	L.F. Fales Machine	Sewing machine modifiers; can sew through 4- to 6-inch material, i. e. , mattresses; tried Teflon coated glass yarn; more abrasive resistance needed.
9.	Fiberglass Industries, Amsterdam, New Amsterdam, N. Y.	Probably are one of the best in needling technology; main business is glass fabrics.
10.	Georgia Duck and Cordage Mill, Scottdale, Ga.	Can make 1/4-inch thick multiple warp, but with thick threads.
11.	Crompton and Knowles, Worcester, Mass.	Loom manufacturers; sells Malimo looms which are 3-D looms, but with limited thickness capacity and presently limited to rather loose fabrics.
12.	J. Harwood and Sons, Inc.	Made hand sewn sample 1-inch thick; can random-wind as in baseball cores.
13.	Institute of Textile Technology, Charlottsville, Va.	Described loom developed for NASA by Goodyear; fabric thickness in excess of 1 foot reported as being possible with this equipment.
14.	Lamports Company, Cleveland, Ohio	Supplier of industrial textiles; were not interested in supplying specialty goods in glass; suggested Prodesco Co.
15.	Leesona Corp., Providence, R. I.	No response.
16.	Lowell Research Institute, Lowell, Mass.	Double-pile fabric in glass-negative results.
17.	Michie Textiles Inc. , Philadelphia, Pa.	Weave special cloth, but not in glass.

18.	Murdock Webbing Co., Central Falls, R. I.	Webbing mfg; received several samples in glass too late to test; multiple-warp fabric of 1/8- to 1/4-inch thickness.
19.	Joseph M. P. Ott Mfg. Go., Pawtucket, R. I.	No reply from this company,
20.	H.K. Porter Co., Pittsburgh, Pa.	Multiple-warp (6 ply) fabric in brass cored asbestos thread; not interested in doing in glass.
21.	Prodesco Co., Perkasi, Pa.	Textile Research company; can make multiwarp fabric and think they can make double pile fabric in glass; cost was outside scope of contract.
22.	Raymond Development Industries, Huntington Park, Calif.	Jacquard hand loom for multiple-warp fabric; received samples relatively loosely woven; relatively low-Z direction thread count.
23.	Saco, Lowell Research and Development Center, Clemson, S. C.	No response.
24.	Schlegel Mfg. Co., Rochester, N. Y.	Make pile fabrics in narrow widths; made double loop fabric in 3-inch width of glass for evaluation; loop density and height can be varied; double-pile fabric more difficult.
25.	Sherman Textile Company, Pawtucket, R. I.	Specialty weavers making 2-ply webb for parachute lines and strapping; learned of them too late to get samples in glass.
26.	Simmons, Henry, Boston, Mass.	Textile Industry Consultant
27.	J. P. Stevens Co., New York, N.Y.	Large cloth manufacturer with large commitment in glass fabrics; made samples of multiple backing tufted fabric, various needled fabrics, and two small pieces of multiple warp knitted fabrics in glass, which were studied.

28.	Textile Buff and Wheel, Chelsea, Mass.	Sews thick layers of cotton cloth for buffing wheels.
29.	U. S. Rubber Co., (Textile Div.), Winnsboro, S. C.	No response.
30.	Valrayco Inc., Pawtucket, R. I.	Braiders; made locked and unlocked samples in glass; larger locked sample ordered, but personnel problems and other commitments prevented delivery.

INDIVIDUALS CONTACTED

1.	Stanley Backer, Prof. of Textile Technology, MIT	Discussions on theoretical aspects of fabric geometry, and a list of persons to contact in various areas of the textile industry.
2.	John Merril, Assoc. Prof. in Textile Technology, LTL; expert in weaving design and technology	Discussed feasibility of multiple warp fabric; answer was yes, if extremely large machines were acceptable.
3.	Albert Woidzik, Assoc. Prof. in Textile Technology, LTI; expert in knitting design and technology	Discussed feasibility of thick knitted fabrics in geometry similar to multiple warp weaving; answer was that such a fabric could not be made by knitting.

While inquiries were given generally a cordial reception, adequate samples of refractory fibers such as glass were very difficult to obtain. Thickness requirements, which started at a minimum of 1 inch so that standard tensile tests could be run, were soon reduced to 1/2 inch and then to 1/4 inch. Of course, modifications in the mechanical test sample design were made to use the thinner samples. Despite the reduction in sample-size requirements, few firms were both willing and able to make samples. The difficulties in obtaining samples of the various candidate techniques are listed below:

a) Not interested in small scale order

b) Not interested if potential business is small or very far in future

c) Do not want to take a chance of harming machine by using such a harsh abrasive material as glass

d) Afraid of time required to develop know-how to work with glass since tensions, abrasion, slip, and stretch of glass are all vastly different from ordinary textile fibers

e) Willing, but want to make development project out of sample preparation, which would be beyond the scope of the contract in time and money

f) Too busy

In general, the textile industry works on such a large scale that even the equipment used for making samples requires considerable manpower operating time. Thus, small-scale operations are neither profitable nor desirable. Of the nine techniques considered, samples adequate for testing were obtained representing five techniques, and samples too small and thin for complete testing were received representing another two methods. The nine techniques considered are listed in Table II, with the companies that supplied the samples listed next to the respective techniques.

Investigation of the potential of the techniques made more headway but also ran into some problems again because of the nature of the textile business. Specific design data were frequently difficult to obtain because business is so competitive that information on apparently trivial modifications was, in many cases, considered proprietary. Thus, and for the following reasons, design data for loom or machine modifications were not included in this report:

a) Where looms or machines are used in standard fashion, a general description is adequate for discussion of fabrication technique and for assessment potential.

TABLE II

TECHNIQUES INVESTIGATED AND SAMPLE SOURCES

Technique	Sample Source
Multiple Warp	J. P. Stevens and Raypan Development Industries
Double Loop	Schlegel Manufacturing Co
Tufted Fabric	J. P. Stevens
"Mali" Process	None
Sew Fabric	H. Harwood & Sons
Knitting	J. P. Stevens
Braiding	Valrayco Inc.
Needling	H. Simmons and J.P. Stevens

b) Where looms or machines are being used in unconventional manner, modifications are almost always proprietary and often Avco personnel are not allowed to see the machines. Notable exceptions to this were American Velvet Company, Stonington, Conn. ; Crompton and Knowles Corp. , Worcester, Mass. ; Schlegel Manufacturing Company, Rochester, N. Y. ; and Sherman Textiles in Pawtucket, R. I.

The discussion of fabric construction methods is arranged so that each technique is described in some detail, and then its potential in making fabric of the required size assessed. Since textile terminology started, or has been borrowed, from the loom, a quite complete description of loom operation and a glossary of pertinent terms is given in Appendix A, and a brief description heads the discussion section of the fabrication methods.

Since almost all of the three-dimensional fabrics under study, except braided and needled materials, are woven in a more or less conventional manner, a brief description of a conventional weaving process will be given, followed by the detailed specific description of each separate fabrication process investigated and a discussion of the potential of each process to make sample fabrics of the maximum size required by the contract statement. This size is basically a cylinder 8 inches in diameter by twelve inches in length.

All weaving is essentially an interlacing of two sets of yarns, and, therefore, almost all looms are similar in their essential parts and corresponding mechanical action. The following description of the operation of the loom is presented to illustrate some of the specific difficulties which will be encountered in the fabrication of **3-D** fabrics.

There are three primary motions on all looms: (1) The dividing of the warp ends (longitudinal yarns) into two groups, known as "Shedding"; (2) the passage of the shuttle containing the filling (lateral yarns) through this opening across the cloth, known as "Picking"; *(3)* and the pushing of the loose filling pick up next to the previous filling pick to form the cloth, known as "Beating-up." In addition, to these primary motions, there are two secondary or contributing motions: The "Let-Off motion," where warp yarn is fed into the loom, and the "Take-up motion," which controls the rate at which the completed cloth is taken away.

For looms of any type to function properly under power, each of these motions must be automatically synchronized so that they work in harmony.

a) Shedding motion. --This motion consists of the separation of all warp yarns into two groups to permit the shuttle to pass through the resulting shed. For some complicated weaves, such as the **3-D,** an attachment known as the Jacquard Head could be used. This equipment allows every warp thread to be controlled independently to produce the desired shedding action. Present loom designs limit the size of the shed when weaving very thick fabrics and hence would impose a thickness limitation on the resulting fabric. The actual thickness of the fabric that could be achieved would have to be determined experimentally and would also be a function of the size of the yarns.

b) Picking motion. --When the shed is formed, the shuttle (carrying the filling) is propelled across the loom through the warp. This is referred to as the "picking" motion. **As** the thickness of the fabric is built up, the position of the shed is raised, requiring the path of the shuttle also to be raised. In the powered operation, this adjustment requires a modification of the equipment, but for the fabrication of initial samples, this motion may be successfully accomplished by hand for the entire thickness of fabric,

c) Beating-up motion. --Consists of pushing the filling pick into the cloth by means of a reed (comb). Where several filling yarns are in a vertical line with each other, some machine adjustments may have to be made for yarns to be struck simultaneously.

1. Multiple-Warp Weaving

a. Fabric Formation

Multiple-warp weaving, as its name implies, is done with a multiplicity of warp ends in the vertical direction as well as in the "plane" of the fabric. A cross-section of such a fabric might look like the sketch in Figure 1. The operation could be done in either of two general ways. The most attractive from the industrial point of view would require all of the shuttles to traverse the fell of the cloth at once, thus giving maximum production rate. This also requires the maximum loom height in the shed area and maximum vertical harness travel since all sheds are made at once. Multiple-warp fabrics for webbing are made in this manner, though the newest high speed machines use spears instead of shuttles to place the filling yarns in the fell of the cloth. These spears are much smaller in cross-section than the shuttles since they carry only a single thread across the fabric instead of a yarn pocket as do the shuttles. The spears act as long sewing needles with the thread caught by a hook so that a double pick is placed at each traverse of the fabric. The much smaller cross-section of the spears requires a much smaller shed for operation. The other loom motions are the same, whether a shuttle or spear is used,

In this geometry, warp yarns (longitudinal) of each fabric layer are mechanically interlocked with the filling yarns of the adjacent layer to produce strength in the direction perpendicular to the surface of the material (radial or *Z*). If requirements should demand, eachlayer can be interlocked with layers deeper in the material instead of, or in addition to, the adjacent layers. Thus, it is seen that the yarns joining each layer in the radial direction form an integral part with the reinforcing yarns in the logitudinal and transverse directions. This geometric feature is desirable from the viewpoint that the transmission of loads from ply to ply does not depend exclusively on the properties of the laminating resin, but is dependent on the mechanical integrity of the reinforcing material itself.

Examples of this weaving technique are shown in Figures 2 through 5. The first two figures show an end view and a top view of the thick multi-warp fabric obtained from Raypan Development Industries, The material thickness is obtained primarily by the use of filling stuffer yarns and therefore is expected to show only a modicum of increase in Z-direction properties. The second two figures illustrate multiple-warp fabrics obtained from J. P. Stevens. The lower material in each photograph is a true multiple warp but only two ply, while the upper fabric is a combination of multiple warp and knitting.

CROSS SECTION OF MULTIPLE WARP FABRIC

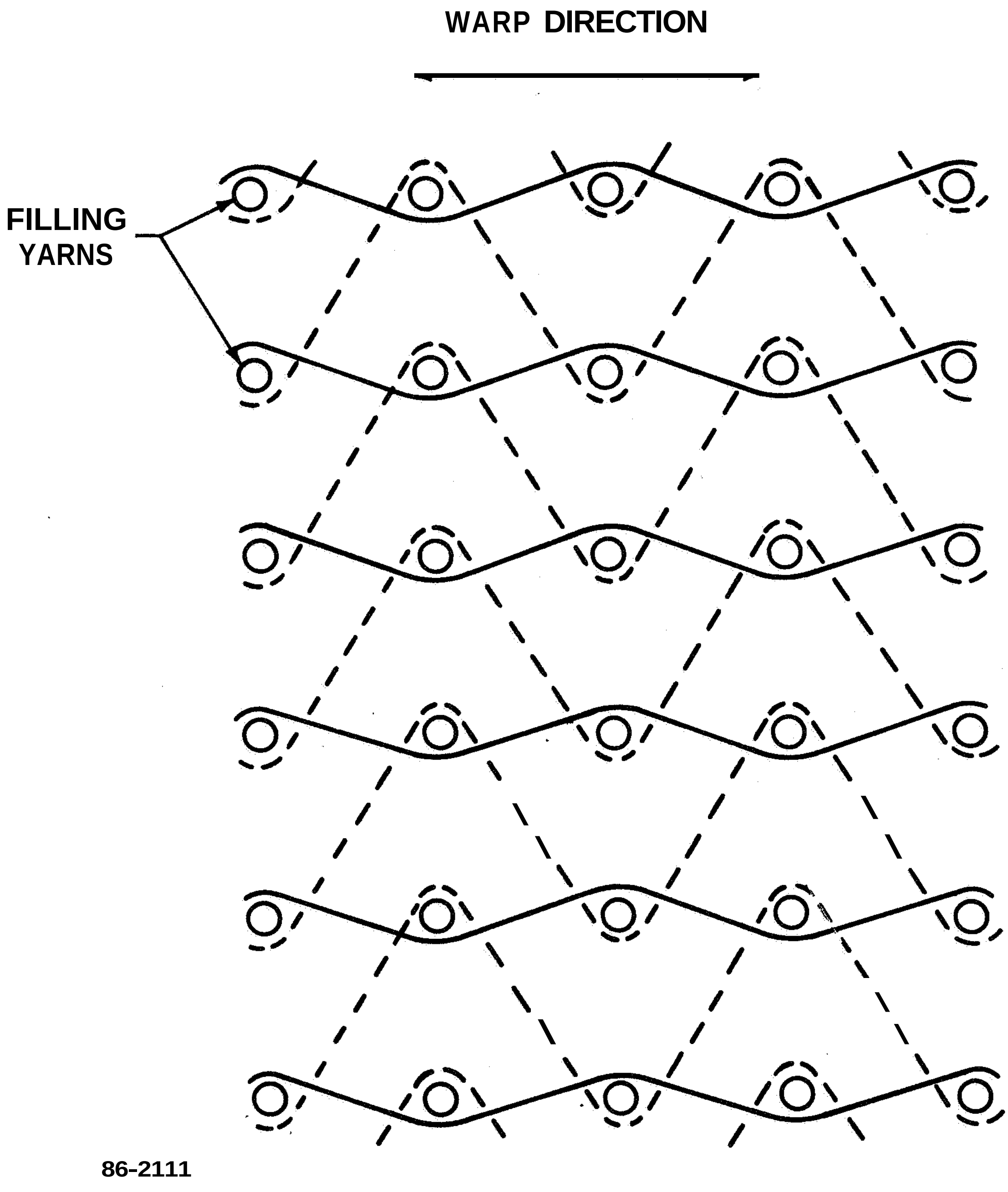


Figure 1 CROSSSECTION DIAGRAM OF MULTIPLE WARP FABRIC

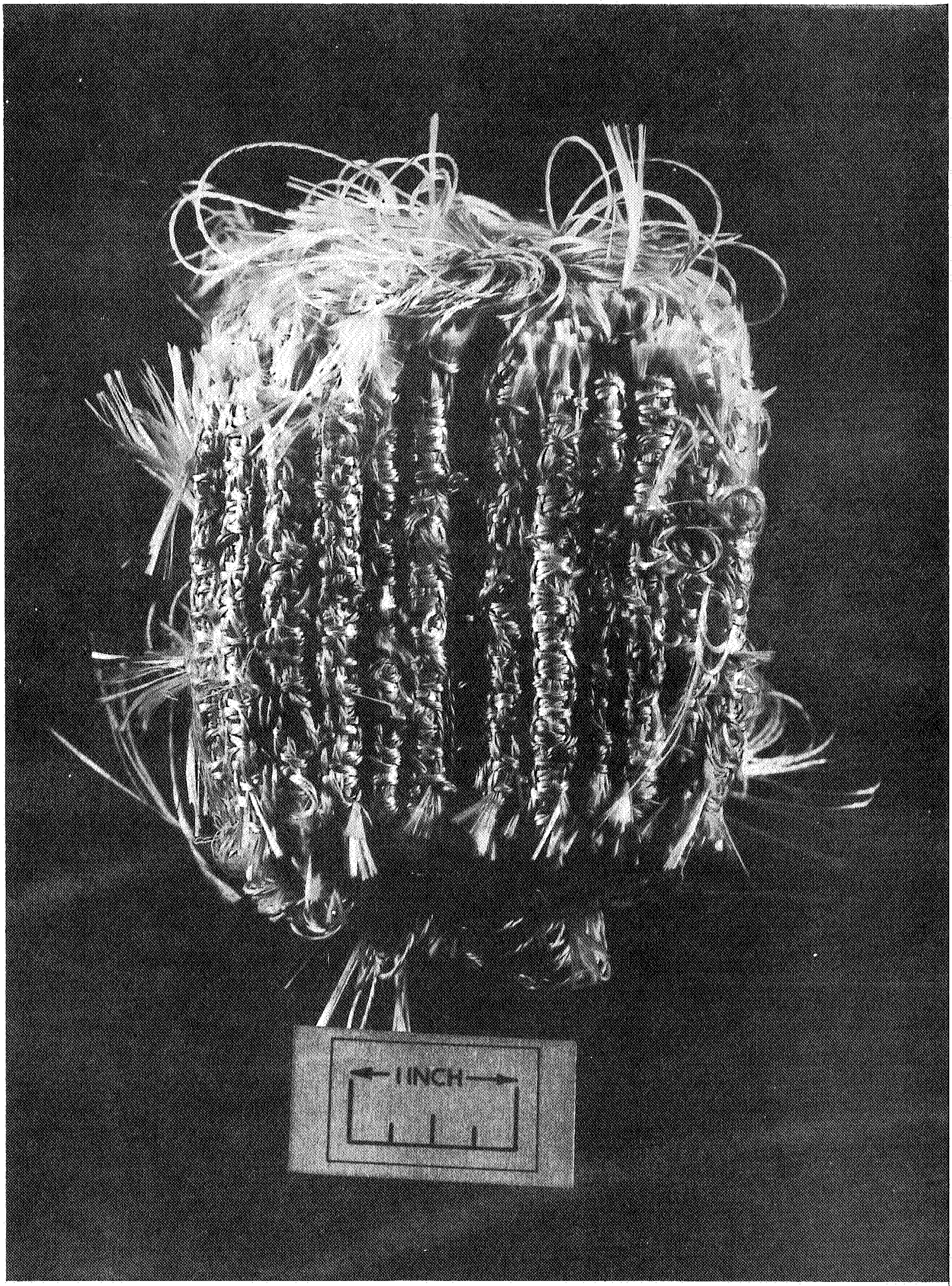


Figure 2 SIDE VIEW OF RAYPAN MULTIPLE WARP FABRIC

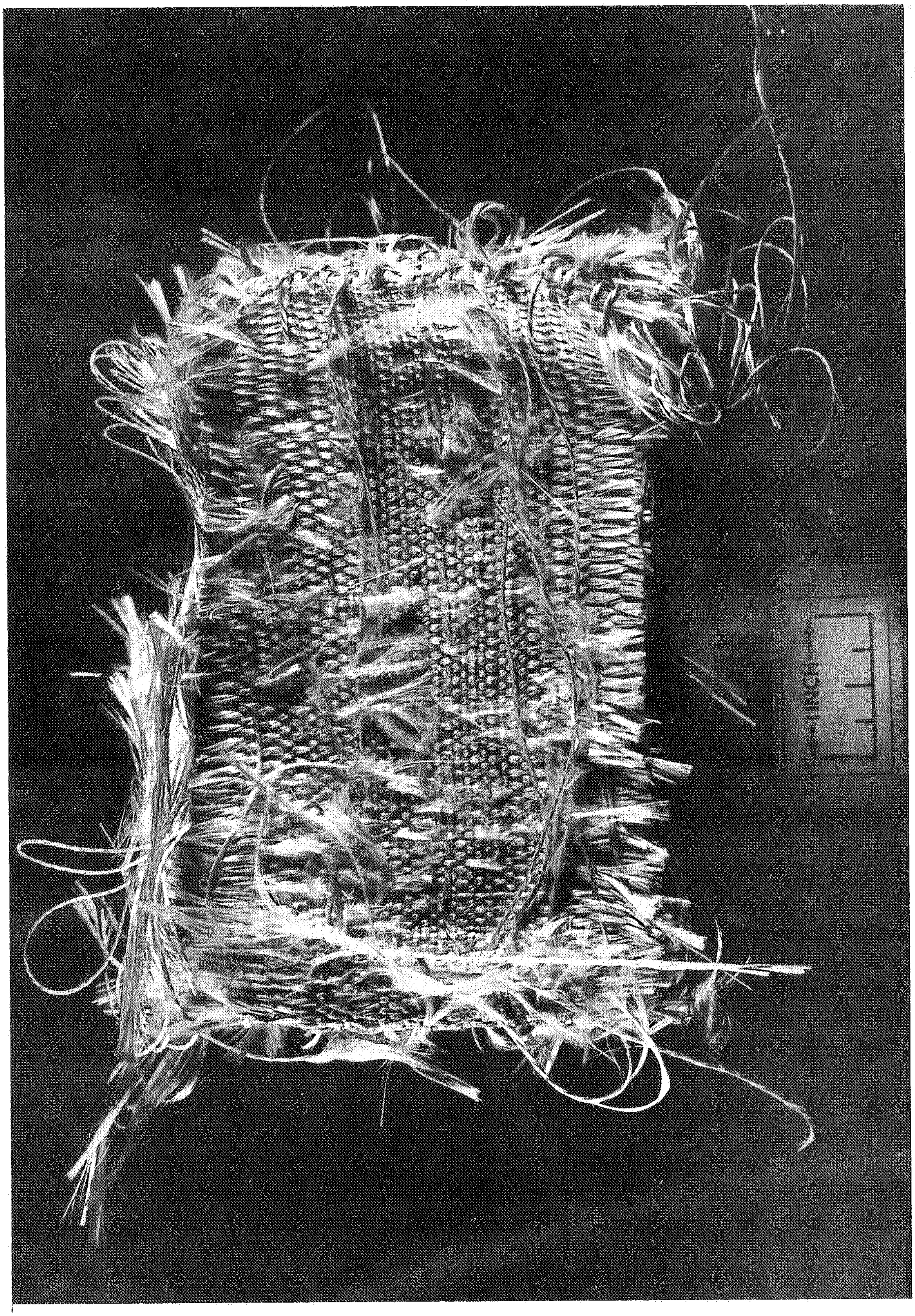


Figure 3 TOP VIEW OF RAYPAN MULTIPLE WARP FABRIC

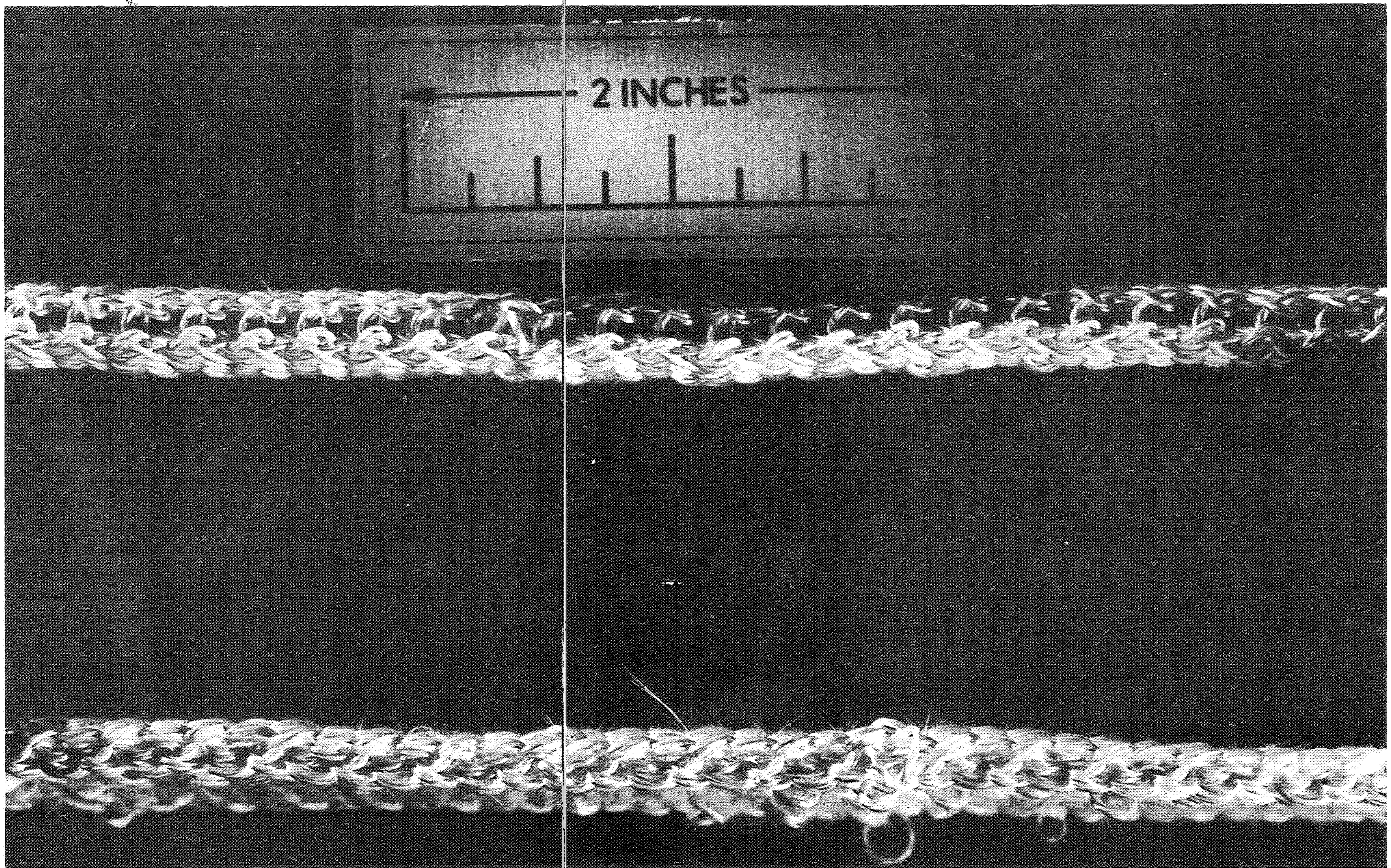


Figure 4 SIDE VIEW OF J. P. STEVENS MULTIPLE WARP FABRICS

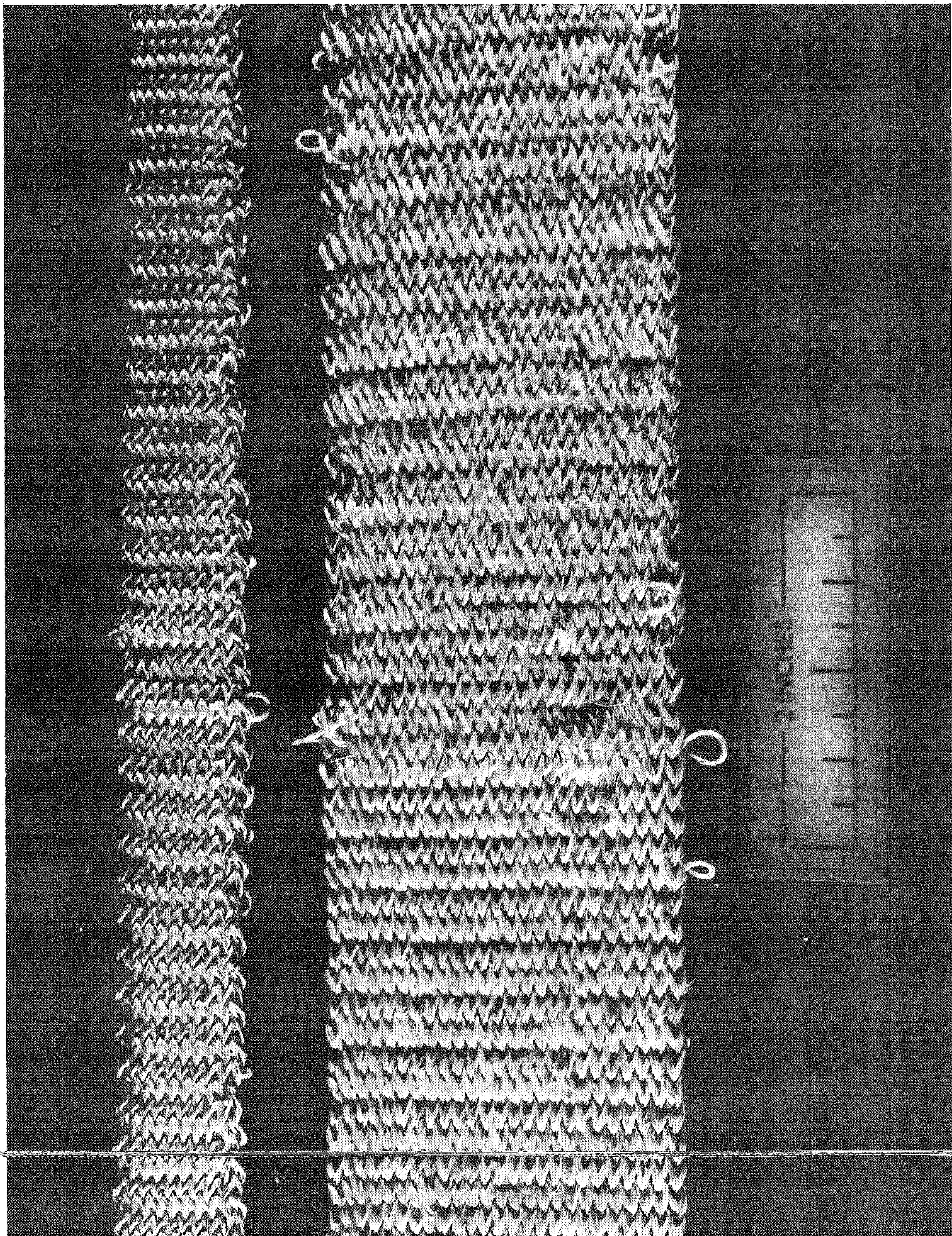


Figure 5 TOP VIEW OF J4 STEVENS MULTIPLE WARP FABRICS

b. Potential

The ability to construct a multiple-warp fabric that exhibits balanced properties with a fine distribution of Z-direction fibers makes this construction a preferred candidate for good ablative properties with high interlaminar strength. Looms are presently available that can weave up to 16 plies with fabrics that range from 1/2 to 1-3/8 inches in thickness. The thickness is dependent upon the yarn size used in weaving the fabrics, i.e., the 1-3/8-inch material is made of 11 plies of asbestos yarn that is 1/16-inch thick. A Jacquard head loom could make even thicker fabrics in narrow widths. However, studies at Avco have indicated that fine threads in a fine weave give better ablative properties than coarse threads in a coarse weave so the thickness figures mentioned above are a little misleading. If threads the size of those in No. 181 cloth are used, then the maximum thickness available from a 32-harness loom is 16 plies at 0.010 inch per ply or about 0.160 inch. A 2600 hook Jacquard loom set up for a 6-inch fabric width at the 57 ends per inch found in 181 cloth would allow only 7-1/2 plies or about 75-mil thickness. By placing two or more ends in each hook as an alternative to using a much larger yarn also produces a much thicker fabric. However, this does not get around the problem that the most desirable geometry appears to be fine threads in a fine network. Nevertheless, some manipulation of yarn dimensions may be possible to increase the loom capacity without significant degradation of ablative properties.

These inherent limitations in the most capacious looms suitable for multiple-warp weaving can be overcome but major loom modifications would be necessary. If thread sizes equivalent to those in 181 cloth are used, then the loom must be increased about 10 times in size to make fabrics about 1-1/2 inches in thickness. This major increase in size must be made in the space between the shuttle raceway and the frame from which the harnesses are controlled (See Figure A-5 in Appendix A). The magnitude of the required size increase for a given fabric thickness can be ameliorated by decreasing the effective size of the shuttle and making the harness thinner.

If the shuttle is made smaller, the size of the shed necessary to permit its travel across the fell of the cloth is decreased in direct proportion, and the necessary harness motion is decreased even more. The latter is true because of the physical displacement of the harness from the reed where the shuttle traverses the shed. Some of the newer looms, particularly for narrow fabrics, have had the shuttle replaced with a rapier or spear, primarily to gain increased speed of operation, but the decreased harness travel is more important for the production of thick multiwarp fabric. Figure A-5 shows that, when multiple harnesses are used, the harness farthest from the reed must travel much more than the harness nearest the reed to maintain the same angle and, thus, spacing in the shed.

If the required motion to form the shed for the spear is only 1/4 that for a shuttle and, the harnesses are made half as thick as normally, then the space required to handle **32** harnesses with shuttles would be large enough to handle about 8 times as many narrow harnesses for operation with spears. While such modifications might be less drastic than complete redesign of the loom, it would still be a major project, requiring maybe \$50,000—\$100,000 and 6 months to a year of time at best. In fact complete redesign may well be better in the long run.

In summary multiple-warp weaving appears capable of fabricating a thick fabric of very good geometry. Modifications of existing looms to get the desired fabric thickness from a fine thread system would require substantial time and money.

C. Prospects of Velvet Looms for **3-D** Fabrics

Weaving velvet requires a more complex loom than flat cloth since two layers of cloth are woven face to face, and then the long nap between is cut. This is in effect a multiple-warp loom since four warps are maintained instead of the usual two. The present machines, of which those at American Velvet Co. are typical, are double-shuttle operated and are therefore only susceptible to certain types of modifications. These modifications are limited in scope and, at the last reach of the modifications aimed at increasing fabric thickness, a fabric balanced in strength in the three orthogonal directions would be practically impossible.

The two fabrics that are woven together may have the nap or tie yarns as long as 1 to 1 1/2 inches in the present machines. This would, however, lead to a very low density of the as-woven fabrics, even if the tie yarn's density and yarn size were increased to the maximum.

In addition, the resulting fabric would be very asymmetric since the majority of the reinforcement would be in the Z direction. Stuffer yarns could be added in the warp direction which would tend to balance the properties and increase the woven density, but these yarns would not be restricted in motion as are the normal warp yarns. The resulting fabric would have very little stability and would still be less dense than desired. The physical handling of this tremendously large number of stuffer yarns, the problem of introducing them to the machine, and the space required to control them in the machine is considered to be nearly impossible of solution at present. Fabrics in the thickness range of

1/8- to 3/16-inch can be made by using stuffer yarns (only two or three per warp end) on the present machines, with the expectation of a stable fabric with high woven density.

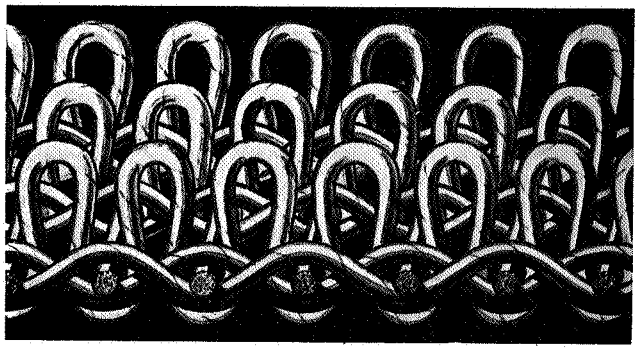
Major modifications are necessary to make thicker, denser, and more balanced fabrics. Certain increases in the fabric thickness could be made by almost hand operation of the loom at a tremendous loss in fabrication speed and increase in manpower costs. Even these changes would be limited to a fabric thickness of 1-1/2 to 2 inches, and the resulting fabric would be very coarse in texture, though probably of quite dense construction, because very thick yarns would be necessary for the weaving. The other modifications would require almost a re-building of the machine to get more space at the shuttle raceway. The vertical height between the shuttle raceway and the frame of the loom from which the harnesses are controlled is the limiting space factor in weaving a thicker fabric. The reed height and the harness motion must also be increased to permit the weaving of a thicker fabric. Such a major modification would cost a minimum of 50 to 100 thousand dollars and several months time. The results, even if positive, would be far from optimum, because of the problem of poor balance in the fabric properties.

2. <u>Double Pile or Loop</u>

a. Double-Loop Fabrication

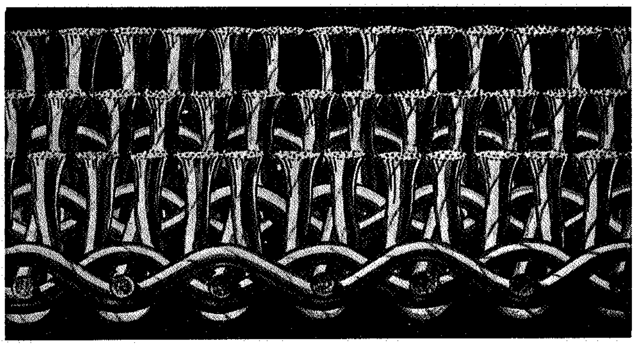
Schlegel Manufacturing Company of Rochester, N. Y., developed a double-loop fabric employing a somewhat different weaving principle than normally used for the single-loop or pile constructions shown in Figures 6 and 7 respectively. The low surface friction of the glass directed the fabric developed to a design that is much less dependent upon this friction for loop size control and fabric stability. The loop threads are alternated in both the warp and fill direction with non-loop threads as shown in Figure 8. These non-loop threads bind in the loops and stabilize the fabric. The finished fabric is shown in Figure 9 both in plane and in cross-section.

With this system the Z direction reinforcement can be varied by changing the size of the loop threads, the density of the loop threads in loops per square inch, and the length of the loops, which controls the loop stiffness. These parameters allow considerable flexibility and control of the Z direction reinforcement. **Also** the loop threads can be made of different material than the non-loop threads for optimization of mechanical strength or ablation performance somewhat independently. Variations in the size and number of non-loop threads provides independent control of hoop and radial strength for tape wrapped parts, which process is one of the most obvious fabrication techniques for this material.



Plain frieze (or uncut pile]. This **has a surface made up entirely of thousands** of **tiny, erect loops.**

Figure6 PLAIN (FRIEZE) UNCUT PILE



Plain cut pile (velvet). This has **a surface** or **"third dimension" made up entirely of fibers standing** on **end.**

Figure 7 PLAIN CUT PILE (VELVET)

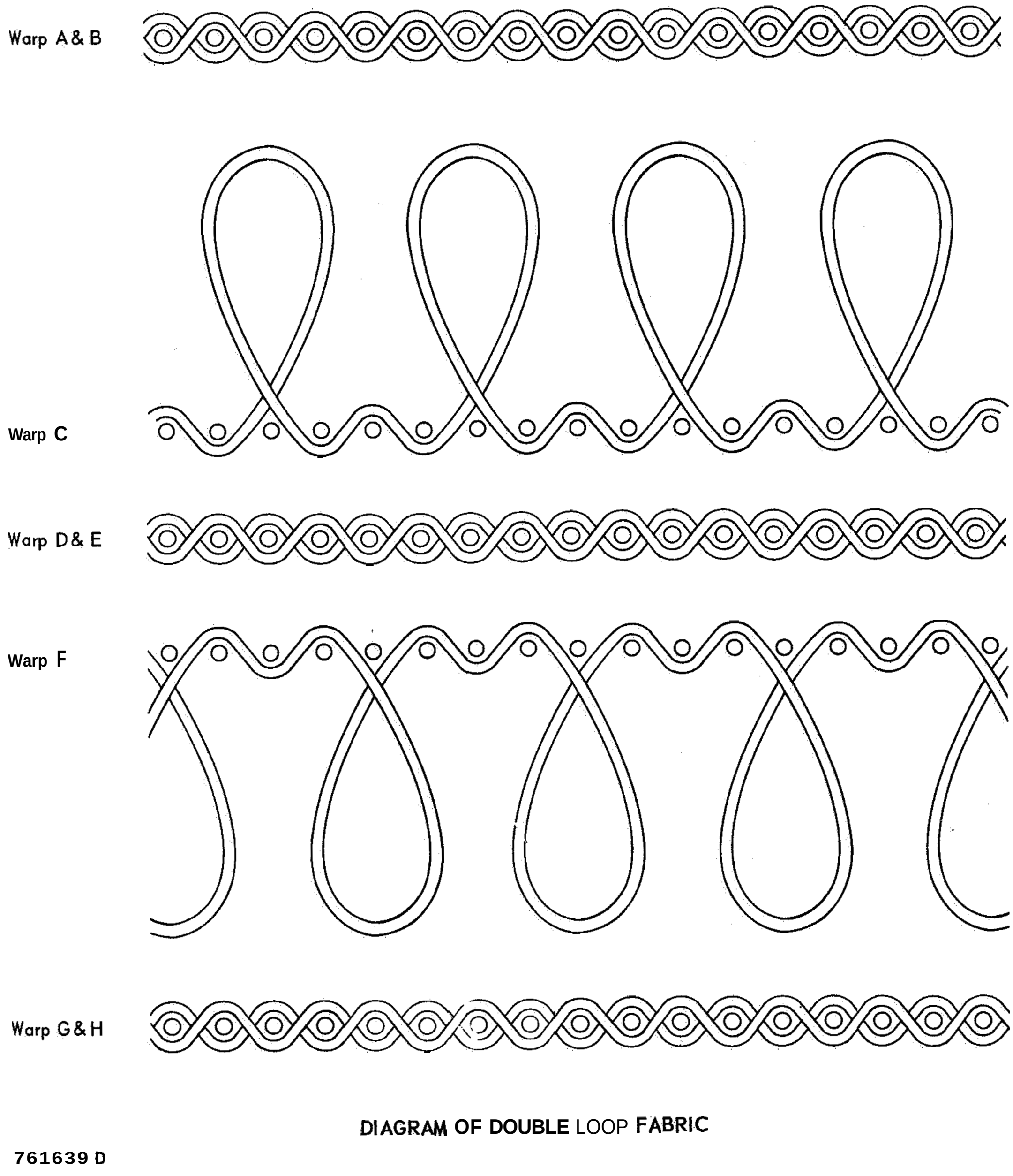


Figure 8 DIAGRAM OF DOUBLE-LOOP FABRIC GEOMETRY

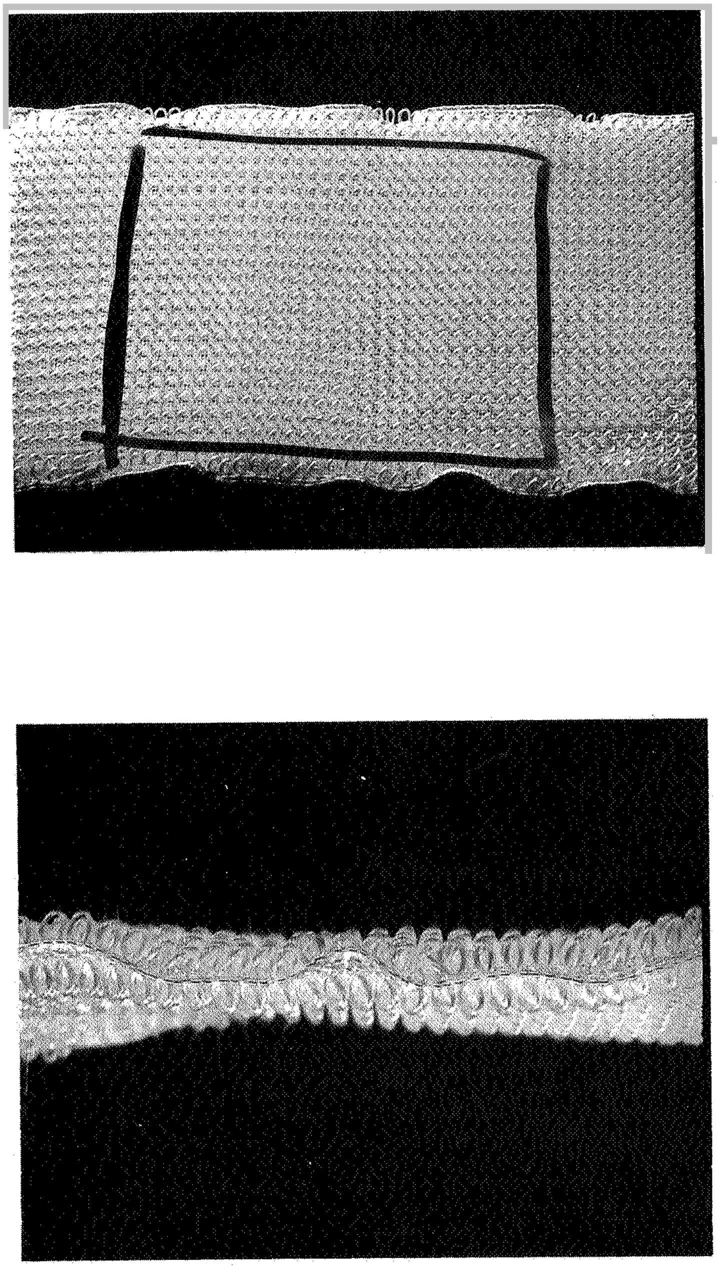


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Figure 9 SIDE AND TOP VIEW OF SCHLEGEL DOUBLE LOOP FABRIC

b. Double-Pile Fabrication

Lowell Technological Institute Research Foundation unsuccessfully attempted to weave a double-pile fabric for Avco. The fabric was processed on their standard toweling loom which is normally used for terrycloth fabrics or towels. The normal yarn used on this loom is cotton. The glass warp beams were prepared and tied onto the existing cotton warp yarns. Two beams or warp layers are required in this operation; one layer provides the basic fabric backing, while the other furnishes the yarn to produce the pile loops.

The pile loops are formed by the action of the reed beating up the pick onto the fell of the cloth. At the same instant that this action is taking place, tension is momentarily released from one of the warp beams so that these yarns are formed into loops just ahead of the reed and locked into place by the interlacing occurring between the pick and the yarns of the other warp layer. It is actually the inter-yarn friction that holds these loops intact once they have been formed, since tension must be reapplied to these looped yarns during the next shedding motion, prior to the insertion of the next pick and set of loops.

Since one cotton yarn has a relatively high coefficient of friction to another cotton yarn, this method of producing a pile fabric works very well for cotton. In contrast, a glass yarn has a very low coefficient of friction when in contact with another glass yarn. For this reason, even through loops could be formed using glass, they immediately pulled out upon re-application of tension for the next shedding action.

The conclusion reached by the Research Foundation was that the glass yarn, as furnished could not be processed into pile fabric on their existing equipment. Two immediate recommendations were (1) improved sizing of the yarn to produce a higher inter-yarn friction or (2) modification of the loom to somehow reduce the tension applied to these loops during shedding. The time involved and the cost of these modifications, with no guarantee of final success, were felt to be sufficient reasons for not pursuing this process any further within the realm of this program.

c. Potential

The fabricability of a double loop or pile material is very high. It shares with needling a very large versatility and flexibility in layup. In fact it has one large advantage over the needled materials, since it can be impregnated before layup. This ensures complete resin penetration with associated increase in strength and reliability due to reduction in unwanted voids. Conventional tape wrapping techniques would handle this material as a prepreg with little or no modification.

The sample from Schlegel shows that it is feasible to make such a fabric with double loops. The fabric geometry, however, is not suitable for a cut pile since the loops ends are not held normal to the fabric plane independently. The loops would be flat if cut open in the usual manner for making a pile fabric. Further the loop height and loop density (loops per square inch) have not been optimized for mechanical strength, nor has the rest of the fabric (non-loop warp and fill) been designed for maximum strength. Despite this, the interlaminar mechanical properties and thermal shock resistance of the laminate are clearly superior to all candidate materials except the Avco 3-D.

Schlegel has said that many of the fabric parameters can be varied in a controlled fashion, some over a rather large range of values. Variations in the loop density, loop height, non-loop warp and fill-thread weight, and the fabric tightness may well improve the mechanical and thermal properties substantially. Nevertheless, a substantial portion of the potential is based on ease of handling and processing, and these areas have not been explored with this fabric. While Avco feels that problems here would not be insurmountable, there is an area of the unknown inherent in the processing.

The best judgement is that despite the unknowns the potential is still very high because of the projected ease of fabrication and the demonstrated good mechanical and thermal properties.

3. <u>Tufting</u>

a. Fabric Formation

A tufted fabric is a pile fabric which is made by inserting face yarn into a ready-made woven backing fabric. This insertion is done by needles, and the inserted tufts are not woven or locked into the backing fabric, but are held in place by the blooming, or untwisting, action of the yarn plus the shrinkage of the backing fabric.

In a cut pile machine (Figure 10), the points of the hooks are turned opposite to the direction of the cloth feed so that the loops feed into the hook. The loop is picked up from the needle in a manner similar to that used in the loop machine, but once the loop is on the hook it cannot get off except by being cut off. As the hook rocks back away from the needle (clockwise as shown in the sketch), the knife rocks up and clips the yarn between the top edge of the knife and the bottom of the hook. These edges are ground to a cutting edge similar to a pair of shears, and the cutting action is also similar to the action of a pair of shears. The hook and knife are both high speed tool steel and the knife is set against the hook under tension. There is also a slight amount of pitch to the knife.

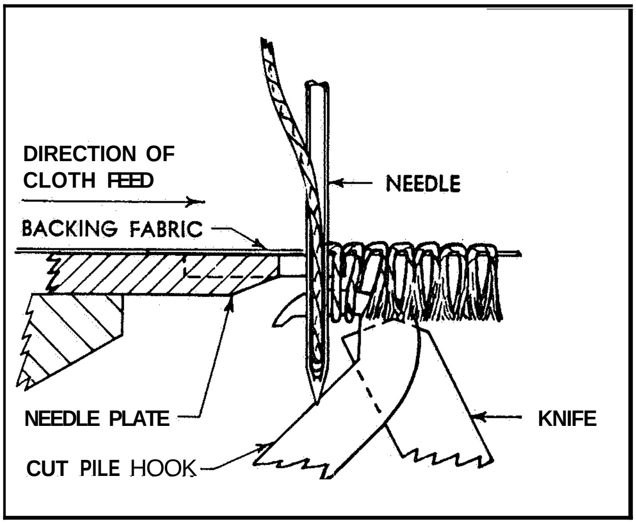

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Figure 10 SKETCH OF CUT-PILE MACHINE

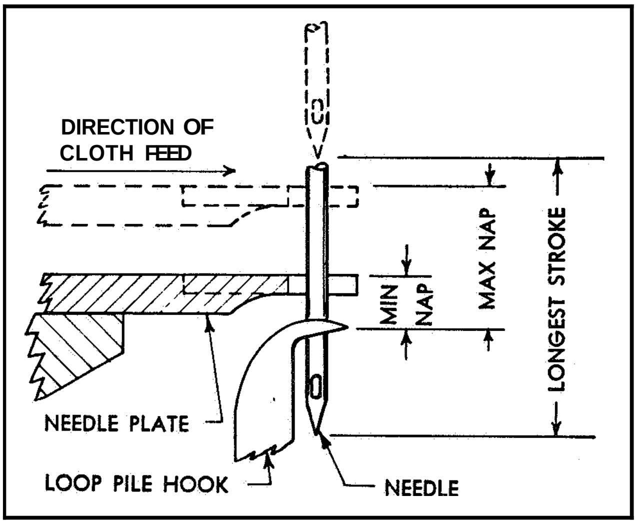

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Figure 11 DIAGRAM OF TUFTING MECHANISM

This sets the point of the knife closer to the hook than the back of the knife; this causes the knife edge to have only a single point contact with the hook edge; and this point of contact moves progressively from the rear to the point of the knife as it closes across the cutting edge of the hook. The hook retains about three loops of yarn at all times. After these have been picked up, the knife cuts one loop in the rear of the hook each time a new loop is picked up **on** the point of the hook.

In a loop pile machine (Figure 11), the needles insert the loop of yarn through the backing fabric and carry it down to a point below the hooks, where the hooks, working in a timed relationship with the needles, cross the needles just above the needle eye and pick up the loop of yarn. The hooks then hold this loop while the needles are being retracted from the cloth, meanwhile rocking back away from the needle path. When the needles start their next descent, the loops have been released from the hooks and the cloth feed has moved forward one stitch length, carrying the loop away from the needle. The yarn feed rolls supply yarn to the needles to prevent the formed loop from being pulled shorter after the hook has released it. In practice, it is customary to shorten the loops about 1/16 inch after their release in order to pull the backstitch down tight against the back of the cloth. This is done by adjusting the yarn feed to feed only enough yarn to make a loop 1/16-inch shorter than the distance from the cloth to the hooks. Note that the points of the hooks are turned in the direction of the cloth feed, and the cloth feeds the loops away from the hooks.

Figures (12 and 13) illustrate the fabric samples made by tufting through 10 and 14 layers of backing respectively. These samples were obtained from J.P. Stevens.

b. Potential

Tufting of multiple-ply backing is presently limited to thicknesses of about 3/8 inch with conventional equipment and staying within the yarn size limitations for best ablation discussed before. J. P. Stevens Company found the maximum number of plies through which they could tuft was fourteen, at which point the abrasion resistance or tensile strength of the tufting thread was not up to the stress of tufting through the large fabric thickness.

Practically all tufting processes start with an open fabric, and the resulting tufted material is quite low in density. See Table V and VIII, and compare 909-62 (14-ply tufted material) and 909-41 (Avco 3-D), which have specific gravities of 0. 90 and 1. 38 respectively. Thus one of the major problems to overcome in addition to trying to make thicker fabrics is that of producing more dense fabrics.

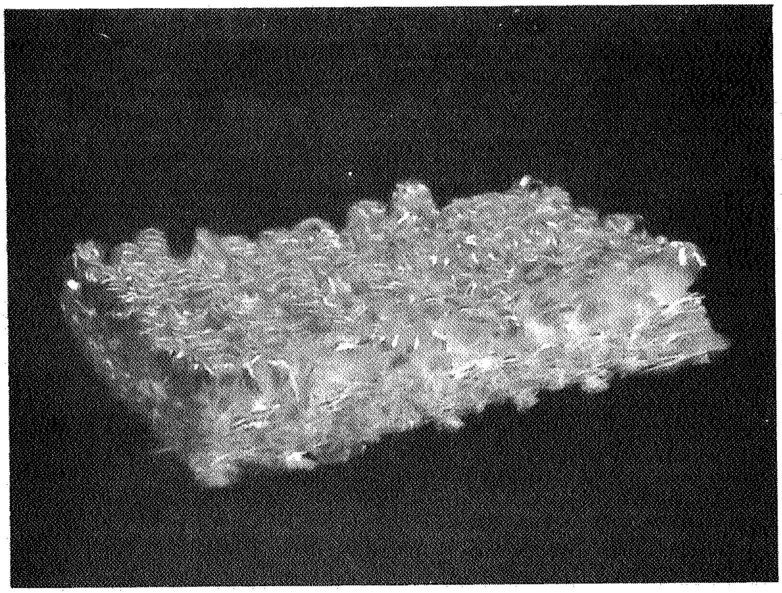

Figure 12 TEN-PLY TUFTED FABRIC FROM J.P. STEVENS

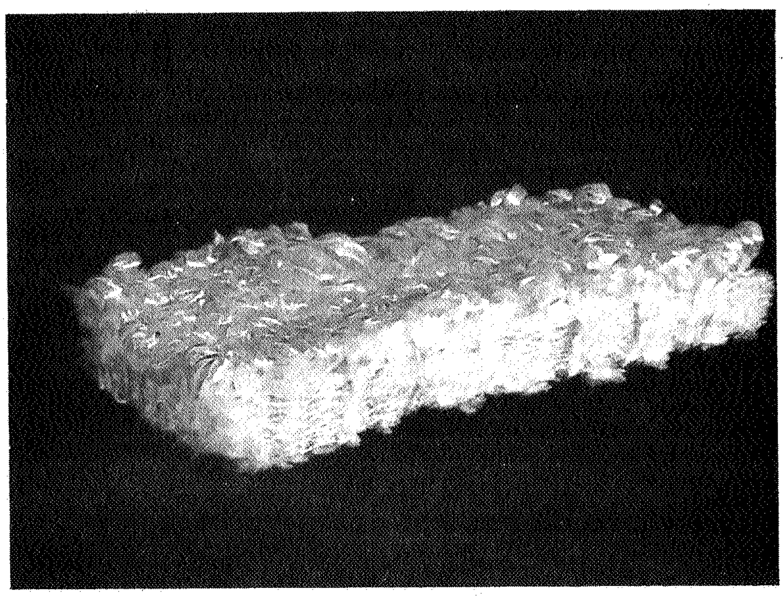

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Figure 13 FOURTEEN-PLY TUFTED FABRIC FROM J.P. STEVENS

The direction that modifications should take to produce more dense fabrics are not all compatible with those that will allow production of thicker fabrics.

A tighter backing fabric will require a smaller tufting needle, which will, in turn, have less stiffness and, therefore, be able to penetrate fewer plies. On the other hand, placing more threads per tuft should increase the tufting threads strength, allowing penetration of more plies and increasing density as well. A more tightly woven fabric would allow more tufts to the inch, in both the warp and fill directions, thereby increasing fabric density, but the greater number of needles per inch would require a significant increase in the stiffness of the needle-holder bar.

The modification of a tufting machine by setting the needles closer together, making the needles and the needle-holder bar stiffer would cost about $50, 000 and require four to six months time to test the feasibility without guarantee of success. This time and money may only buy us a fabric 3/4- to 1-inch thick if successful. A very recent development of the Cobble Division of the Singer Company could make the tufting process much more attractive. This new method of tufting uses compressed air to move the tufting thread into the base fabric through a hollow needle. Thus practically all the abrasive action involved in the normal tufting process has been eliminated. How well the new process would work through a large number of plies is not known, but a fabric thickness of more than 2 inches would require a needle stiffness that may be unattainable. Also the present fixed needle bar stroke of 1/2-inch would probably be inadequate for very thick multiple-ply backing.

Thus the tufting process has only a low potential with the possible exception of the Honesty loom of Singer to make fabrics in the 8-inch thickness bracket.

4. <u>"Mali" Process an Malimo Loom</u>

a. Fabric Formation

The "Mali" process for making cloth is very recent, machines having been in production only since 1958; its introduction into the United States is even more recent. These factors prevented us from obtaining fabrics in glass until the last month of the program, and even then the fabrics were so thin that they were unsuitable for testing. Thus this evaluation is based almost exclusively on a visit to Crompton & Knowles-Malimo, Inc., the sole agent in the U.S. for this method.

The Malimo machine forms fabrics from yarns, which fabrics, by and large, are designed to have woven characteristics. Figure 14 illustrates

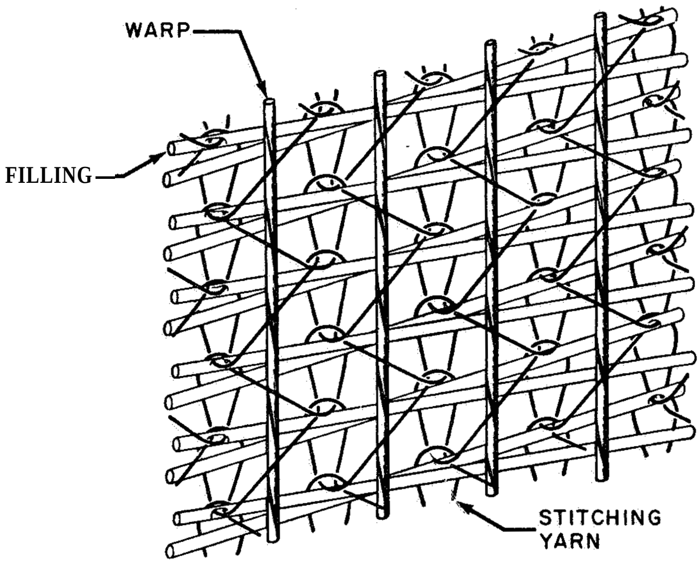


Figure 14 DIAGRAM OF MALIMO STRUCTURE

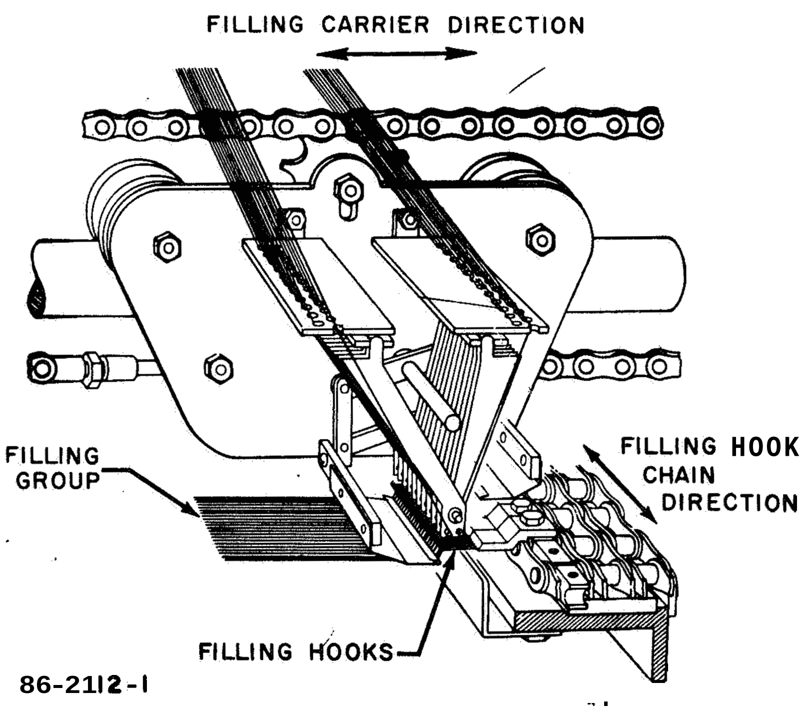


Figure 15 DIAGRAM OF MALIMO FILLING OPERATION

a typical Malimo structure, consisting of two layers of overlapping filling, a superimposed straight warp thread, and a stitching thread in interlocking chain stitch, or tricot stitch, interlacing the two systems. The existence of warp and filling lends woven characteristics to the structure, with the following basic design possibilities:

1) A predominant yarn count in warp and filling is shown in Figure 14, together with a thin stitching thread, i. e., a fine synthetic or rayon filament will result in a fabric with a woven look, since warp and filling dominate and the stitching thread almost vanishes from the fabric, both in relative yarn content as well as in appearance

2) In structures with approximately equal count between all three systems, the woven look is maintained on the top side of the fabric, as shown in Figure 14, and a knit look begins to appear on the back-side. All three yarn systems in this case contribute materially to the total fabric weight and are distributed approximately in the following proportions: warp, 1 part; filling, 3 parts; stitching thread, 4 to 4 1/2 parts.

3) Should a very predominant stitching thread be chosen, with a light warp and filling, the fabric assumes a distinct knit look but maintains its woven characteristics.

Apart from the aforementioned, a number of conventional or novel yarn color effects can be incorporated in such basic structures. Acceptable fabrics are made with only stitching and filling thread, with the warp eliminated, and then a choice between the tricot stitch shown and a plain chain stitch is available.

The basic principle of the machine incorporates the multiple laying of filling and the preparation of a filling sheet as the first step in the fabric-forming process. This permits a by-passing of the loom principle of one pick at a time, no longer making fabric-forming speed dependent on filling insertion or fabric width. Figure 15 shows the laying of the filling by means of a filling carrier moving intermittently from side to side in the machine, conveying a multiple number of filling ends (up to 144) coming from a creel to the machine. The carrier, from a dwell position on one side, gradually accelerates to its highest speed in the center, with gradual deceleration to the dwell position on the other side. This provides for the most gentle filling insertion. On either side of the machine there is a filling transport chain moving continuously towards the front of the machine. As can be seen in Figure 15, at the moment of dwell of the carrier over the filling-chain hooks, a pressure foot brings all filling ends into contact with the chains, and the continuous motion of the chains cause each end to be wrapped around one hook. The intermittent motion of the carrier, together with the continuous motion of the chain, provides for the arrangement of 2 layers of filling superimposed on top of each other in the fabric, which possess equal density throughout. The angle of filling insertion can be made to vary, depending on the relative speeds of the filling carrier, bandwidth, and chain speed; this angle is in the area of 2 to 5 degrees under standard conditions.

In Figure 16, the filling sheet is shown traveling continuously toward the fabric-forming position, held on either side by the filling-carrying hooks. The warp ends are laid on top of the sheet by means of stationary guides arranged according to the gage of the machine. The stitching elements consist of a compound needle with an independently moving closing wire rather than a latch. The front guide bar lays the stitching yarns into the stitching needles and, for the tricot stitch shown, performs a figure-8 motion.

The stitching can take place at up to 1400 stitches per minute, and the fabric production speed is solely a function of stitching speed and individual stitch length. During the particular phase of the stitching process illustrated in Figure 16, the stitching needles are open, having pierced through the filling and warp layers. The stitching guide bar presents the stitching thread to the open needle, and the previous loop has been pushed back onto the needle shaft by the thread layers. In subsequent steps, the needle is retracting and closing, the sinkers cause an interlock to be formed by casting off the previous stitch over the yarn enclosed in the needle eye. With the forward motion of the stitching needle and its opening, the new loop is pushed back on the needle shaft. For the tricot stitch, each stitching yarn works alternately with two needles; for a plain chain stitch, the front guide bar makes a circular motion, causingeach end to be presented to the same needle only. The filling hook chains also carry the formed fabric away from the fabric-forming position, and a take-off roller removes this fabric from the chains. Since all filling is laid continuously into the fabric, a firm selvage is formed.

The arrangement of the working elements and yarns in the Malimo machines may be studied further in Figure 17.

Depending on the number of needles and warp guides per 25mm, fabrics of different weight classes are produced; correspondingly the machines are classed according to their gage. There are presently in existence machines with 3 1/2, 7, 10, 14 and 18 gage, and finer gages are in preparation. Standard fabric weights for a 14-gage machine might range from about 8 to 20 ounces per square yard, depending on the counts and filling density used.

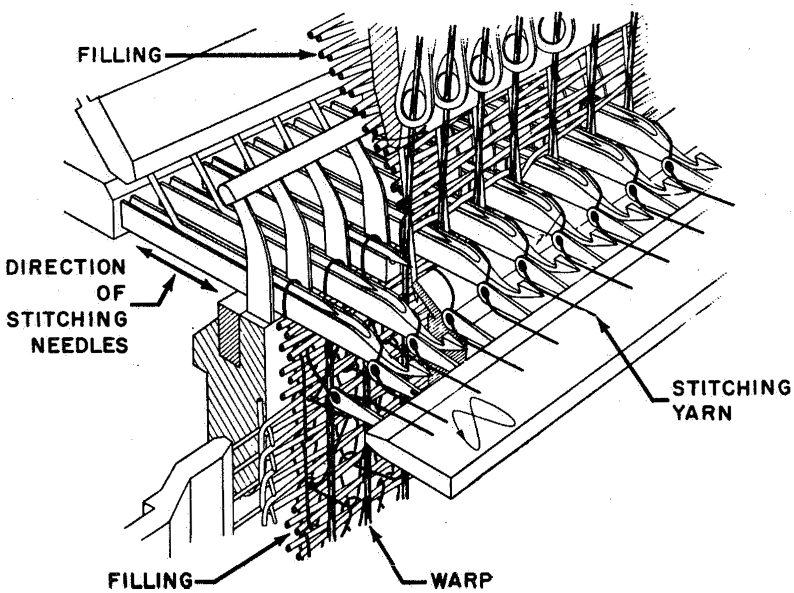


Figure 16 DIAGRAM OF MALIMO STITCHING OPERATION

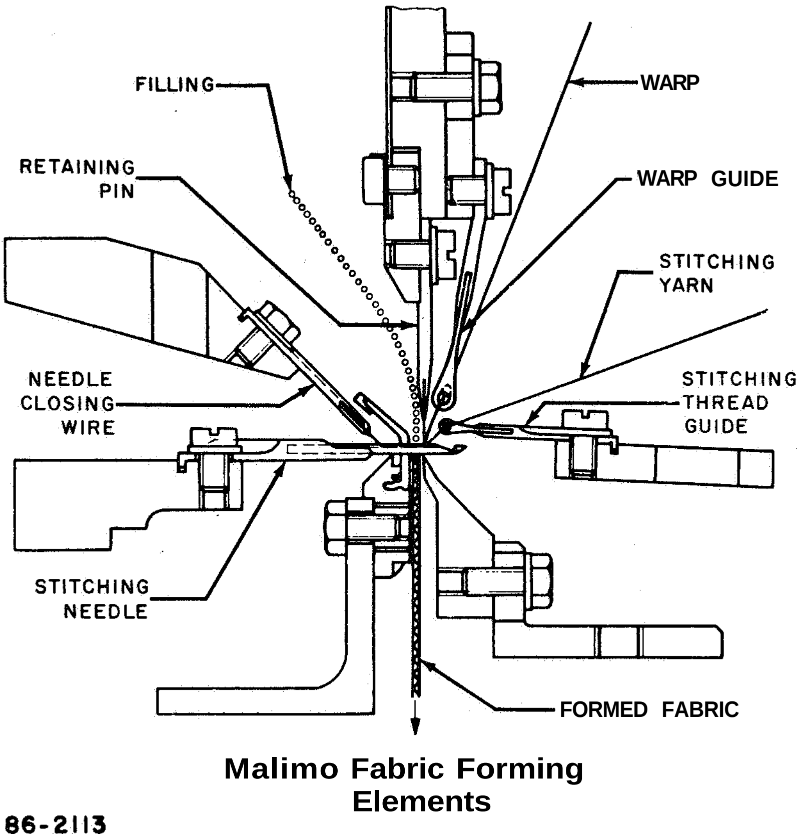


Figure 17 DIAGRAM OF MALIMO FABRIC FORMING ELEMENTS

b. Potential of Malimo Machine

Since the "Mali" process for making cloth is so new (the first commerical machines in operation as late as 1958), the limitations and potential are not as well known as for other more conventional methods. Specific limitations of the present machines due to physical dimensions can be discussed and an intermediate level of potential for this method indicated. Present machines are limited in cloth thickness by the gap between the metal fabric guides. This space limits the cloth to about 3/8 inch. The needle length establishes the next size barrier if the gap mentioned above is widened. This length restriction has two steps. The first is the length of the needle shank not normally imbedded in the metal casting and limits the thickness to about 5/8 inch, while the second step is the inherent stiffness in the needle, which would limit the amount of the needle shank that has to be imbedded to prevent bending. The bending torque is a function of speed of operation, so if the speed is lowered less bending torque would appear and a thicker fabric would be possible. Present estimates by the Crompton and Knowles engineers, sole representatives in the U. S., indicate the maximum thickness might be in the range of 3 to 4 inches of thickness. This is just within the low end of the range of interest, and therefore the potential is considered to be of intermediate level.

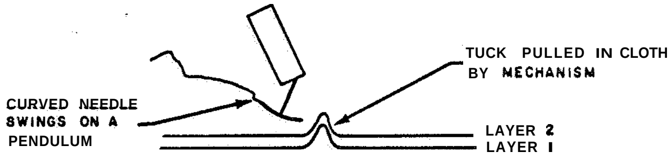
5. Sewing Together Existing Fabrics

a. Fabric Formation

Sewing together a multiple of existing woven fabrics is a technique with which everyone is familiar. The degree of difficulty of sewing, however, increases tremendously as the number of fabrics or total thickness to be sewn is increased. There are basically two methods of approach here: (1) stack the total layers of fabric to be sewn on top of each other, and sew them together with a "standard" machine; or (2) sew one layer to another layer, and then consecutively sew one layer at a time to those already sewn until the desired height is reached.

Both of these techniques contain different mechanical limitations when a height of 3/4 to 1 inch is reached, however, and both result in a common major fabric deterioration. The "standard" machine obviously becomes limited in daylight opening, horsepower, and needle strength. Specially designed equipment can overcome the first two limitations, but needle strength presents a more complex problem. Needle supports, as well as improvement of needle material and temper, would increase needle strength to a certain degree. One eventually, however; must increase the diameter of the needle to increase its strength. This dictates a coarser sewing construction, or fewer stitches per unit area, as well as increasing the yarn severance occurring in the base fabrics.

In the second sewing technique, based on the principle of "blindstitching," sewing is done solely from one side of the cloth, with no need to penetrate through the entire thickness of cloth layers, as is true of the "standard" technique. The sketch below shows the general features of this type of stitch.



BLIND STITCHING

The limitation in height here is imposed by the inability of the sewn fabric to form the necessary tuck once a certain thickness has been attained, due to the increase in fabric boardiness or stiffness as its thickness is increased. Again, the major disadvantage of the resultant fabric is yarn severance occurring in the basic fabrics.

Yarn severance of the basic fabrics obviously decreases the tensile strength significantly in the X, Y plane of the final composite. The insidious factor about this yarn severance problem is that one usually can not see it occurring, since the sewing thread holds the severed yarns in place and tends to cover up the problem. Actual testing of the samples is usually required to determine the degree to which yarn severance has occurred.

(Figures 18 and 19) show a side and top view respectively of a hand sewn sample obtained from H. Harwood & Sons.

b. Potential

Sewing has a limited potential with existing machines because the sewing thread is pushed through the fabric outside the needle and is therefore subjected to maximum abrasive action. The sewn samples obtained during the program and the attempts by vendors to make sewn samples were plagued by thread breaks due to the low abrasion resistance of the glass. Present machines are limited to 2 to 3 inches in the dense fabrics desired for nozzle fabrication. Hand sewing reduces abrasion

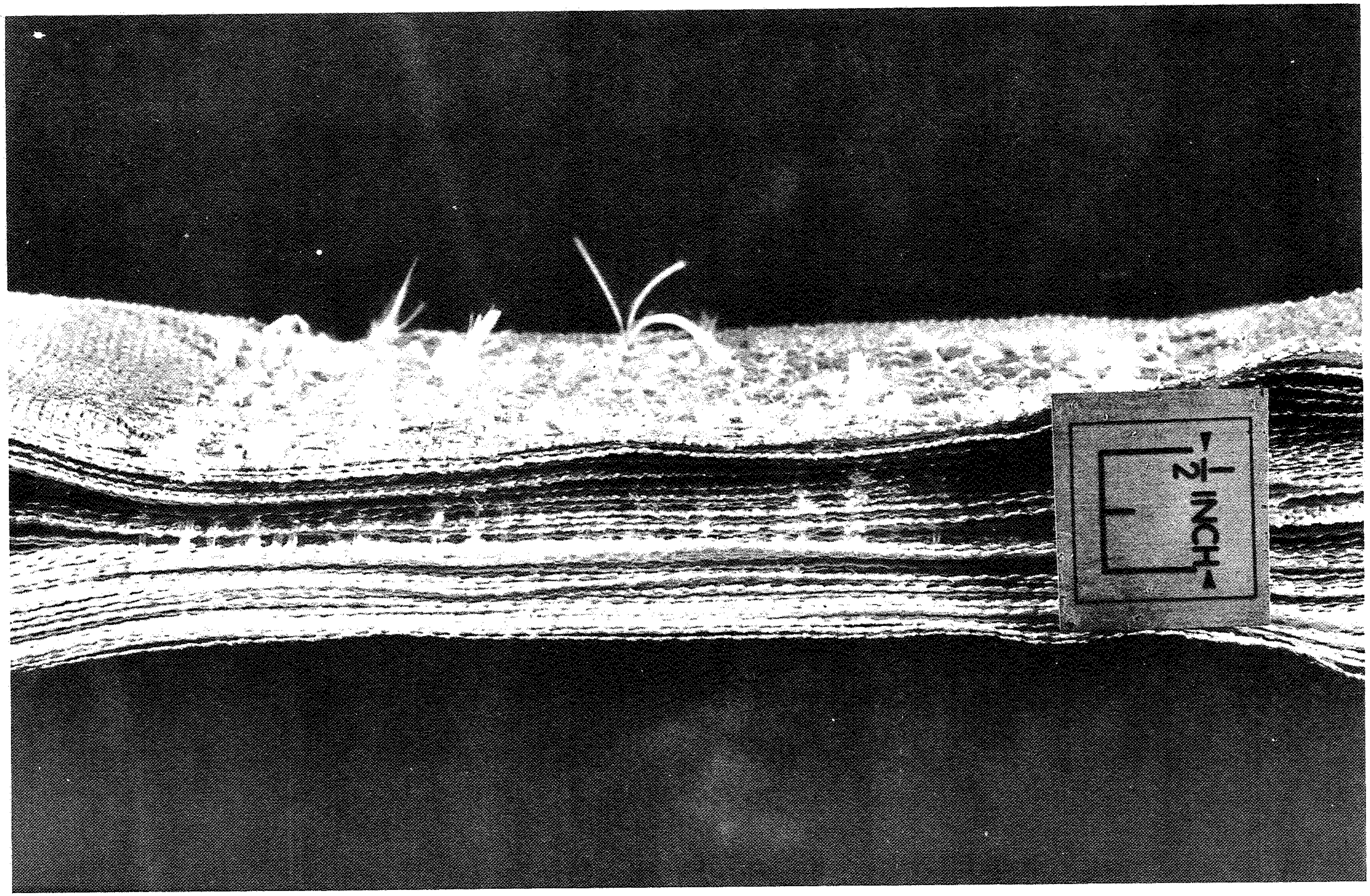


Figure 18 SIDE VIEW OF HAND-SEWN FABRIC FROM H. HARWOOD AND SONS

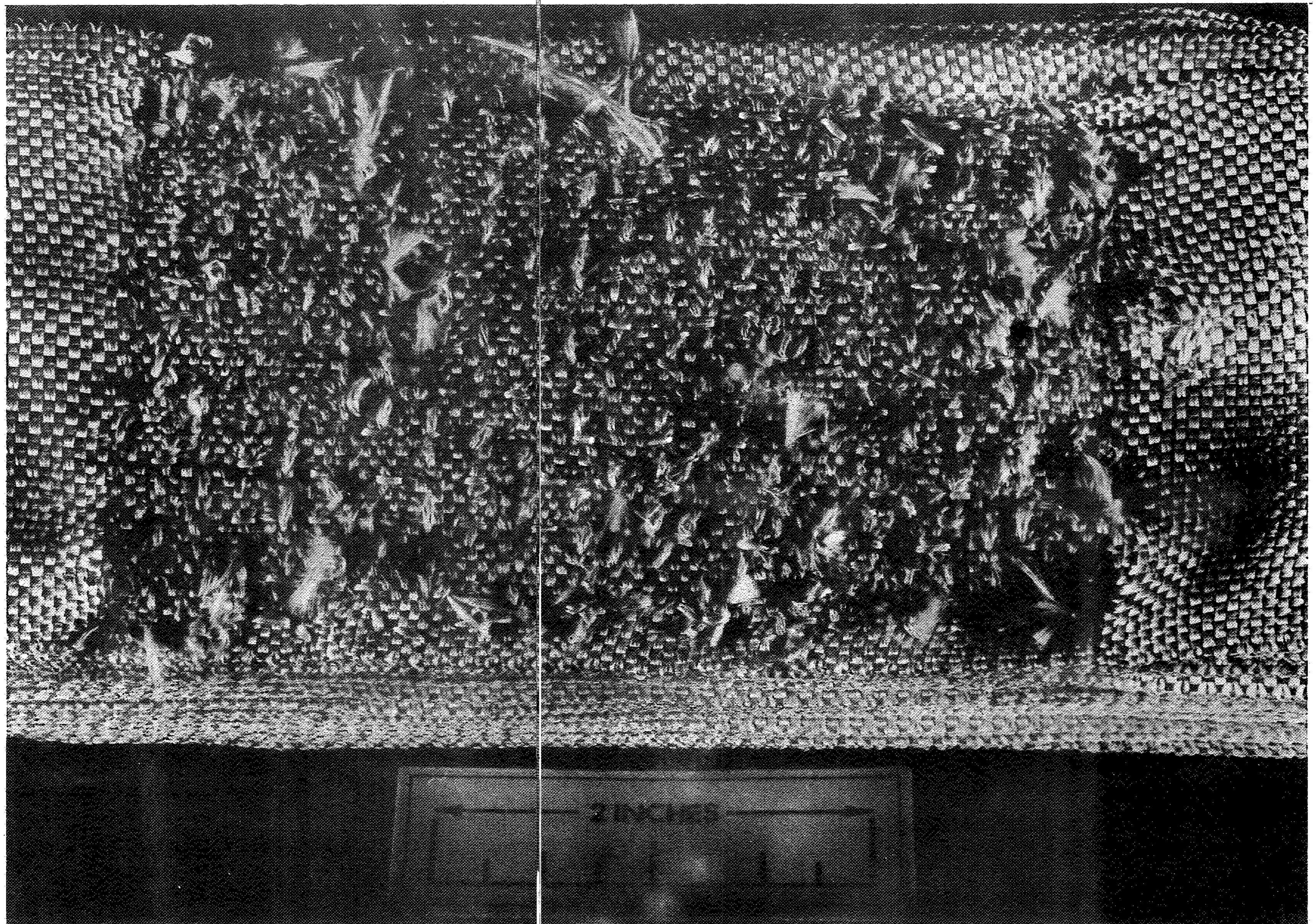


Figure 19 TOP VIEW OF HAND-SEWN FABRIC FROM H. HARWOOD AND SONS

because of the gentle handling and minimum tensions involved. Problem areas are the maintenance of even tension in the Z direction reinforcement, the ability to get high concentration and homogenous distribution of the Z direction reinforcement, and the very questionable status of reproducibility in this technique.

All in all, the prognosis is poor for samples of good and reproducible quality in the sizes required.

6. Knitted Textile Fabrics

a. Fabric Formation

To most people, knitted fabric is somewhat of an unknown quantity. Few people can distinguish it readily from woven fabric. Fewer still have any conception of how it is produced. The reason for this, primarily, is that knitted fabric has huddled too long in the shadow of its woven counterpart. Now at long last it appears to be coming into its rightful spot in the textile limelight.

Knitted fabric differs vastly from woven and nonwoven fabric. Woven fabric is formed by the interlacing of a series of lengthwise and crosswise threads. Nonwoven fabric is produced by bonding webs or layers of fibers. hitting, in its simplest form, consists of forming loops of yarn with the aid of thin pointed shafts and drawing other new loops through those previously formed. This interlooping and the continuous formation of more loops into each other produces the knitted fabric structure. In machine knitting, a multiplicity of needles, needle holders, and yarn feeds replaces the pins, hands, and fingers of hand knitting. The type and kind of fabric is determined by the order of the interlocking: whether the loop is carried to the front or to the back of the fabric or on both sides; whether the fabric consists of whole loops or half loops formed singularly or in mass; and whether the fabric consists of warp yarns or weft yarns. When a crochet hook is used instead of knitting pins, individual loops are joined, successively or intermittently, into the sides of previously formed chain loops, and a hand-made, warp-knit fabric is produced.

In the formation of knitted fabric, two different methods may be employed: (1) weft knitting and (2) warp knitting. In weft knitting a single thread of yarn is fed at a time to a multiplicity of needles in a weft or crosswise direction, whereas, in warp knitting, a series of yarns are fed vertically to the knitting needles -- one to each needle.

A knitted fabric consists throughout its entire structure of a multiplicity of loops and loop linkages that are bound into each other, ahead and behind, to the right and to the left. Thus, a normal loop consists of two joined "S" forms. This double "S" structure follows all through the fabric, whether it is knitted on weft or warp knitting machines. The only difference between the two systems of looped fabric formation exists in yarn linkages from loop to loop. If these follow continuous "S" paths we get elasticity. If cross linkages occur, elasticity is lessened, according to the extent of their number, all the way to firmness and comparative inelasticity.

If the "S" linkages are jointed into "S's" of adjacent wales, a run-proof fabric results; but, if only into the same wales, run-resist fabric is made. Additional run-resist properties are achieved in the latter by tight knitting of some tuck-float fabrics.

Of course, all these factors are dependent upon the use of the proper yarn size for the needle size and spacing, i. e., the yarn-for-gage and the wales-and-courses-balance principles of fabric making. If a too thin yarn is used, a sleazy fabric results. If, on the other hand, a thinner yarn is used and the courses are piled into the fabric, a boardy fabric results.

Regardless of type, whether warp or weft knit, knitted fabrics generally fall into two kinds, depending upon whether the machine used to make them contained one or two sets of needles.

Fabrics are usually flat stitch or rib stitch, i. e., plain knit or ribbed knit. A third kind, the purl stitch, exists, but this is not generally used as a basic over-all fabric stitch. Except for some imitation hand knit garments for infants, the purl stitch is more often used to produce self-color pattern effects and, then, in combination with either the flat or rib stitch.

b. Potential

Knitting has the lowest potential of any method considered for several reasons.

1) Knitted fabrics, no matter how tightly made, are inherently high elongation loose fabrics.

2) Present machinery can knit two-ply fabrics as a maximum: thus thickness with reasonable yarn size is out of the question without very expensive and time consuming machine development having little chance of success.

3) The lack of abrasion resistance of glass has prevented fabrication of knitted fabrics until the recent introduction of beto glass. This much finer denier filament is not available in Refrasil or quartz, and, in addition, the ability of beto glass to withstand the higher abrasion of knitting multiple-ply fabrics is unknown.

These problems all militate against further consideration of this reinforcement fabrication method, despite its advantageous ability to make fabrics in almost any shape desired, e.g. hosiery. Therefore this method was eliminated as a candidate interlaminar reinforcement technique.

7. Braiding

a. Fabric Formation

Braiding is essentially a technique for weaving in a cylindrical shape. Figure 20 shows a typical normal braid supplied in glass by Valrayco, of Pawtucket, Rhode Island, which was tested as a control material for the interlocked braid to be supplied by the same company. The interlocked braid, as described below, was not delivered because of a combination of manpower, production, and technological problems.

Figure 21 is a photograph of a typical braiding machine. This sample is composed of layers of helically wound and interlocked yarns, one layer on top of another but with no interlock occurring between one layer and the next.

The sample that Valrayco attempted would have contained an interlock between all layers at every point of intersection of the helically wound yarn. Figure 22 is a photograph of a smaller sample showing three interlocking techniques. The sample order would have contained either type 1 or 3 interlocks, The finer the helical yarns, the closer together can be their intersections, and, consequently, the more numerous can be the layer to layer interlocks in the axial direction. The number of interlocks around a circumference is limited by the machine and inside diameter of the tube. For this reason the sample would have contained the finest (smallest) yarns, helically, that are consistent with practical machine operation. The sample would have had 12 interlocks per circumference, which is the particular machine capacity, though other machines can make up to 96 interlocks per circumference. If the ratio of O.D. to I.D. desired is too large, a braided fabric would have to be started on a small machine, which would limit circumferential interlocks, and then be moved to a larger machine to bring it up to final O.D. if circumferential interlocks per inch were to be held as constant as possible.

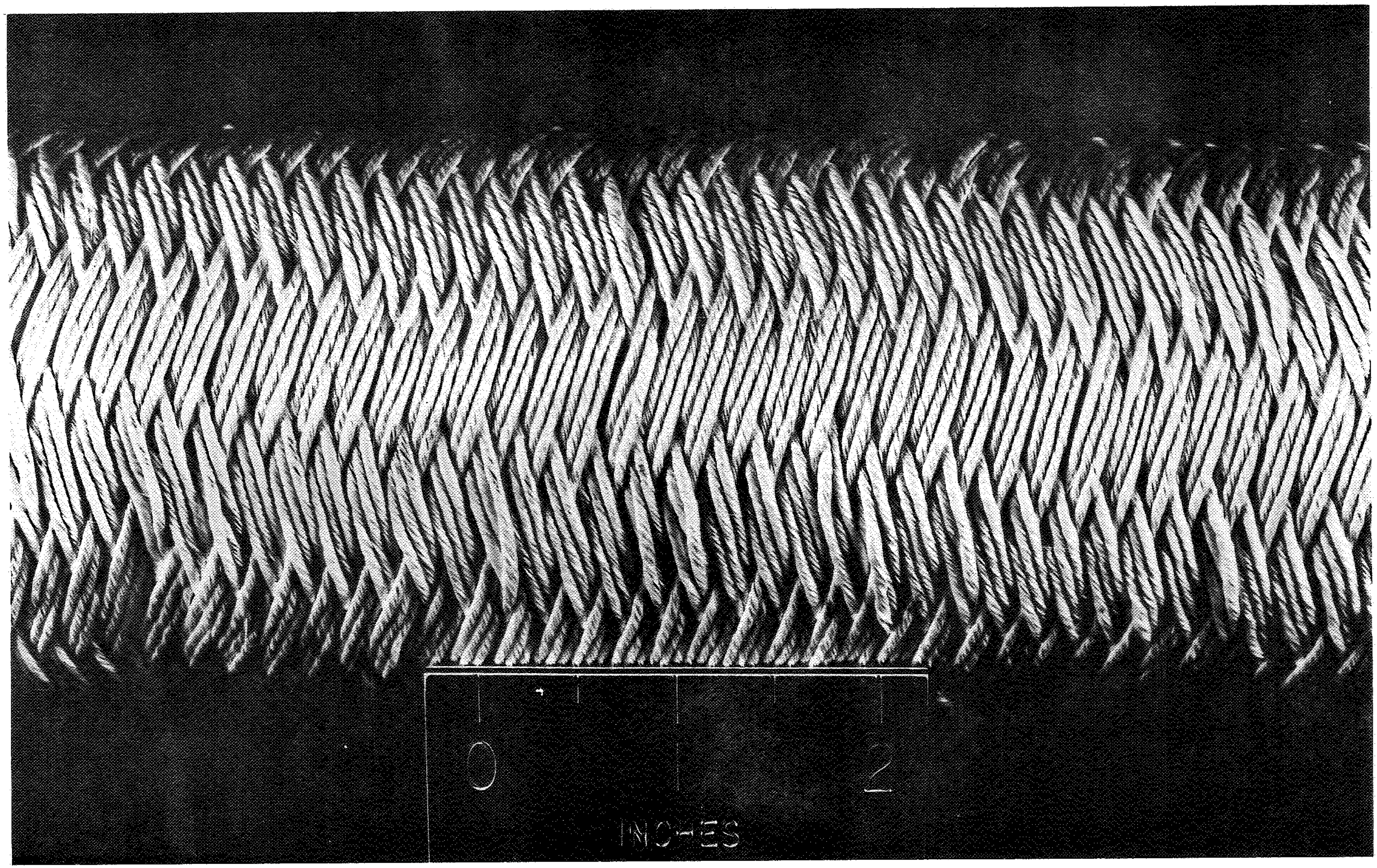


Figure 20 NORMAL BRAID FROM VALRAYCO

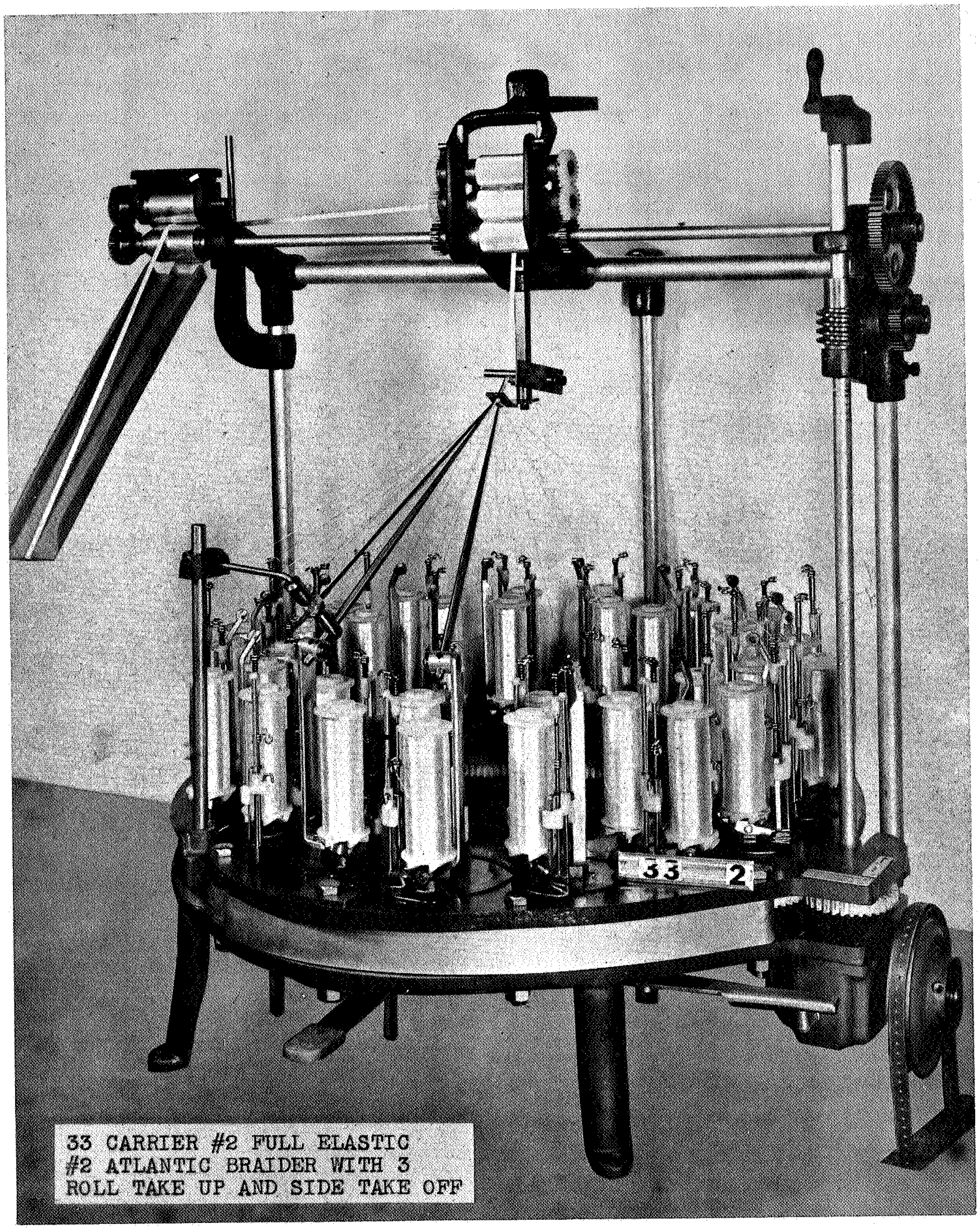


Figure 21 TYPICAL BRAIDING MACHINE

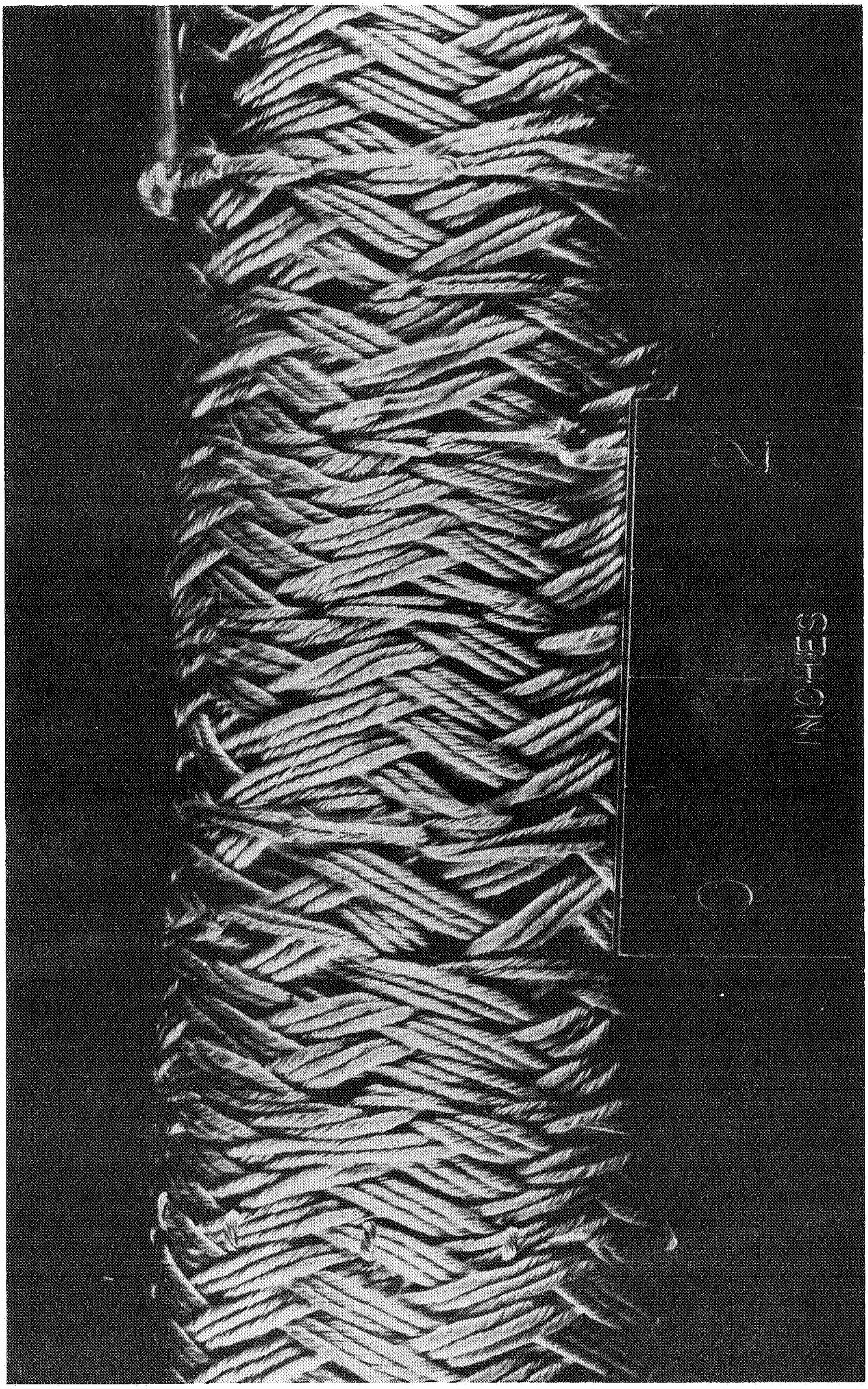


Figure 22 INTERLOCKED BRAIDED SAMPLE FROM VAL MAYCO

b. Potential

Conventional braiding has some of the flexibility in form that knitting has but almost none of the restrictions on thickness. The braided samples that were tested had a wall thickness of about 1 inch and much thicker samples could have been made. The mechanical properties of this sample were poor because the weave was not tight despite a fabric specific gravity of 1.34, and the individual yarns were so large that resin pockets were distributed throughout the impregnated composite. The problem of tightness is a function of the smoothness of the glass fibers and would require work to optimize a finish that would give an optimum between stability of fabric and ease of operation. Smaller yarns could be used readily at the expense of wall thickness per travel through the braider. Repeat runs through the braider could make almost unlimited wall thickness. By varying the tension in the yarns, the tightness can be controlled and, thus, the resin content of the resulting composite.

Interlocked braid is inherently a cylindrical-coordinate sewed fabric, both having geometrical advantages as well as disadvantages. The interlocks are made in a radial direction, and thus the density of radial fibers increase from exterior of the cylinder to the interior. Thus the maximum interlaminar strength is automatically built into the region where the thermal shock is highest and most needed. On the other hand, the interlocks are inserted from the inside of the cylinder so the space and density of sites is limited. Present machine capacity for a 1-inch I. D. cylinder is about 16 interlocks per square inch of inside surface (12 interlocks per circumference). Machines presently made could give 96 interlocks per circumference, but generally these are high-speed, large machines that manufacturers are reluctant to take out of production for sample pieces, especially glass pieces, No estimates on cost or time required are available for the operation of these machines.

The potential of the interlocked braid technique is the least defined of all methods examined. Only poor samples of unlocked braid were available for testing, and extrapolation from these results are impossible. The attempts to make more favorable samples were stymied by man-power problems and by the handling problems associated with the glass. The best estimate of the potential is that the method does not have the flexibility of needling; nor does it appear to have the strength potential of the best systems.

8. <u>Needled Felt Fabrics</u>

a. Fabric Formation

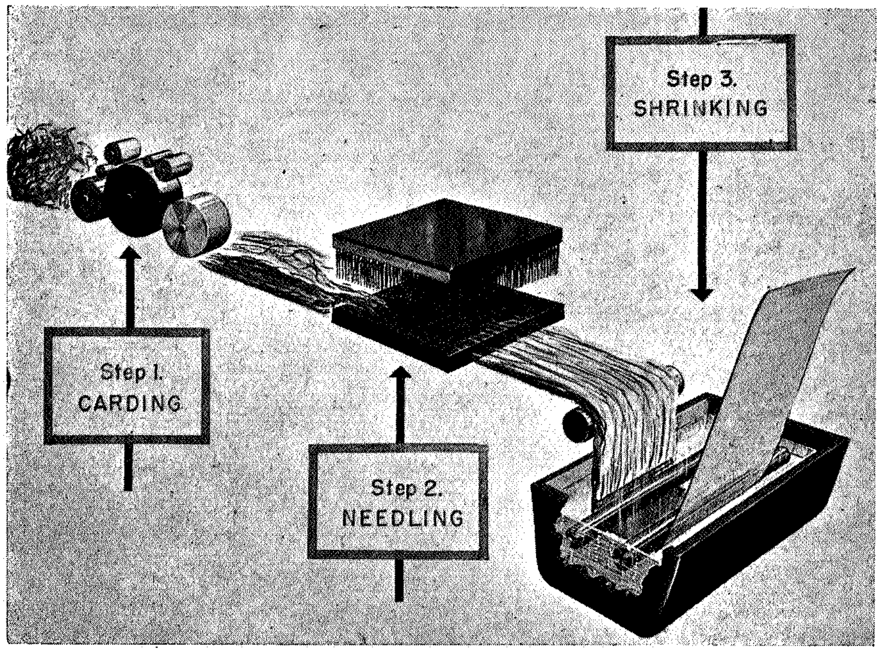
A versatile textile material for industrial and apparel uses, felt is characterized by intimate, three-dimensional fiber entanglement. The resultant high frictional forces provide excellent fabric integrity and particularly high splitting resistance to delamination. The three-dimensional nature of fiber entanglement distinguishes felt from felt-like nonwoven structures where the entanglement is mostly two-dimensional. In the felt-like materials, the weaker frictional forces must be supplemented by bonding adhesion between fibers and between layers of fibers to achieve fabric integrity. Felt can be produced in almost any desired weight, thickness, and density. The fact that it can be made to rigid specifications and tolerances over wide ranges of properties makes felt ideal as an engineering material. Until recently, it was believed that felt could be made only from wool or fur by a process involving carding, hardening, and fulling.

In 1952, it was discovered at DuPont that felt could be prepared from synthetic fibers by a new process involving carding, needle punching, and shrinking and is shown diagramatically in Figure 23.

A batt is prepared either by means of cards or garnetts and crosser-lappers or by air deposition methods. This batt is passed through a needle-punching machine which contains a reciprocating crosshead holding many barbed needles. As the needles move in and out of the batt, they complete the three-dimensional fiber entanglement which gives the structure its unique fabric cohesion. Uniformity of fiber alinement in length and width of the batt is important in producing uniform tensile properties.

The needle-punched batt may then be subjected to a shrinking treatment, which causes further compacting and strengthening of the felt. The degree of density and hardness is controlled by the amount of needle punching and by the fiber shrinkage. Close tolerances are possible.

A variation of this technique is afforded by alternating fabric and felt, using the same process. The needling of felt technique involves placing alternate layers of fabric and felt in a textile "needling" machine and forcing felt fibers into and through the fabric in a plane perpendicular to the fabric. The needling device consists of a large number of needles attached perpendicular to a board, which in turn can be actuated up and down to pierce felt and fabric placed beneath it. The needles contain small barbs on their exterior surface so that as they pass through the felt they carry fibers along with them. If the needles continue into a



The three steps in making synthetic fiber felt. (Courtesy *Textile Research Journal*)

Figure 23 DIAGRAM OF FELTING OPERATION

piece of fabric, then the felt is mechanically linked to the fabric by hundreds of small fibers. Successive layers of felt and fabric processed one on top of another by this method produces a billet containing horizontal layers linked together by felt fibers. (See below.)

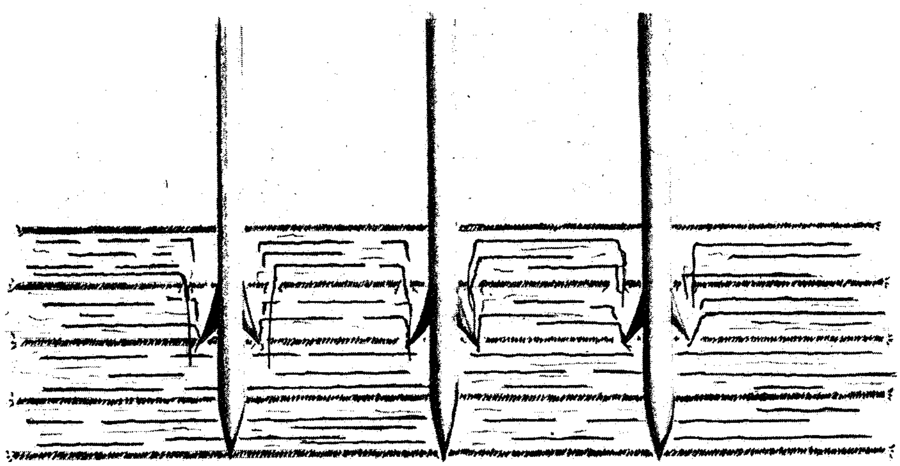


Figure 24 NEEDLED STRUCTURE

Figures 25 and 26 illustrate the Z direction fiber content of the needled samples purchased from J. P. Stevens. The variation in the needling parameters used to make the six samples from J.P. Stevens are listed in Table III. Figures 27 and 28 show a top and side view respectively of a material made by needling alternating layers of matt and fabric.

TABLE III

NEEDLING PARAMETERS FOR FABRICS FROM J.P. STEVENS

Sample No.	Needle Penetration [inch)	No. of Penetrations per inch	Weight of Resultant Fabric (lb/yd^2)
1	3/8	50	14.75
2	3/4	50	20.5
3	1/4	40	20.0
4	1/2	100	14.0
5*	1/2	175	23.5
6*	max. possible 1/2 t	175	26.5

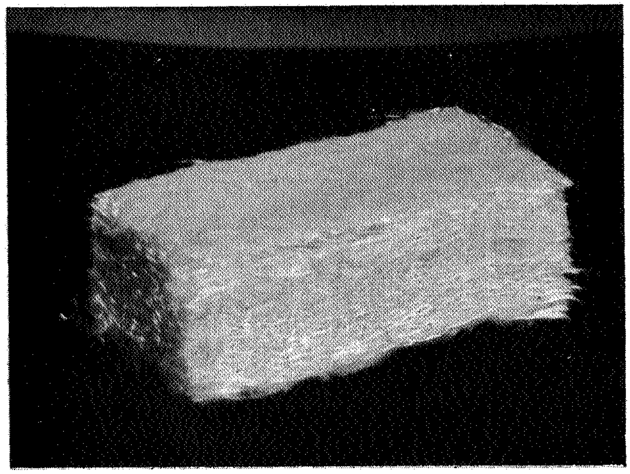


Figure 25 PHOTO CROSS-SECTION, TRIAL NO. 1, NEEDLED STRUCTURE FROM J.P. STEVENS

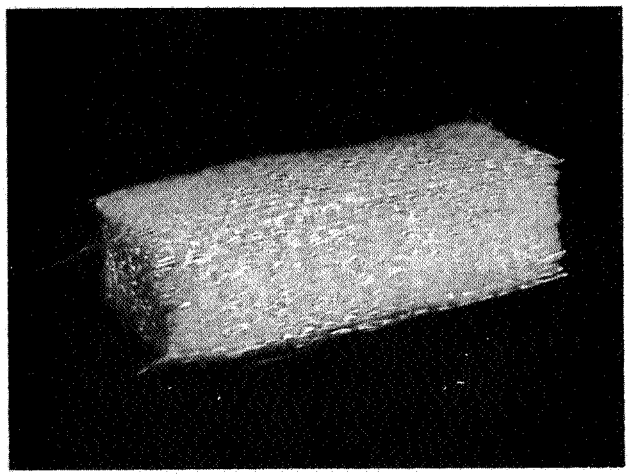


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Figure 26 PHOTO CROSS-SECTION, TRIAL NO. 5, NEEDLED STRUCTURE FROM J.P. STEVENS

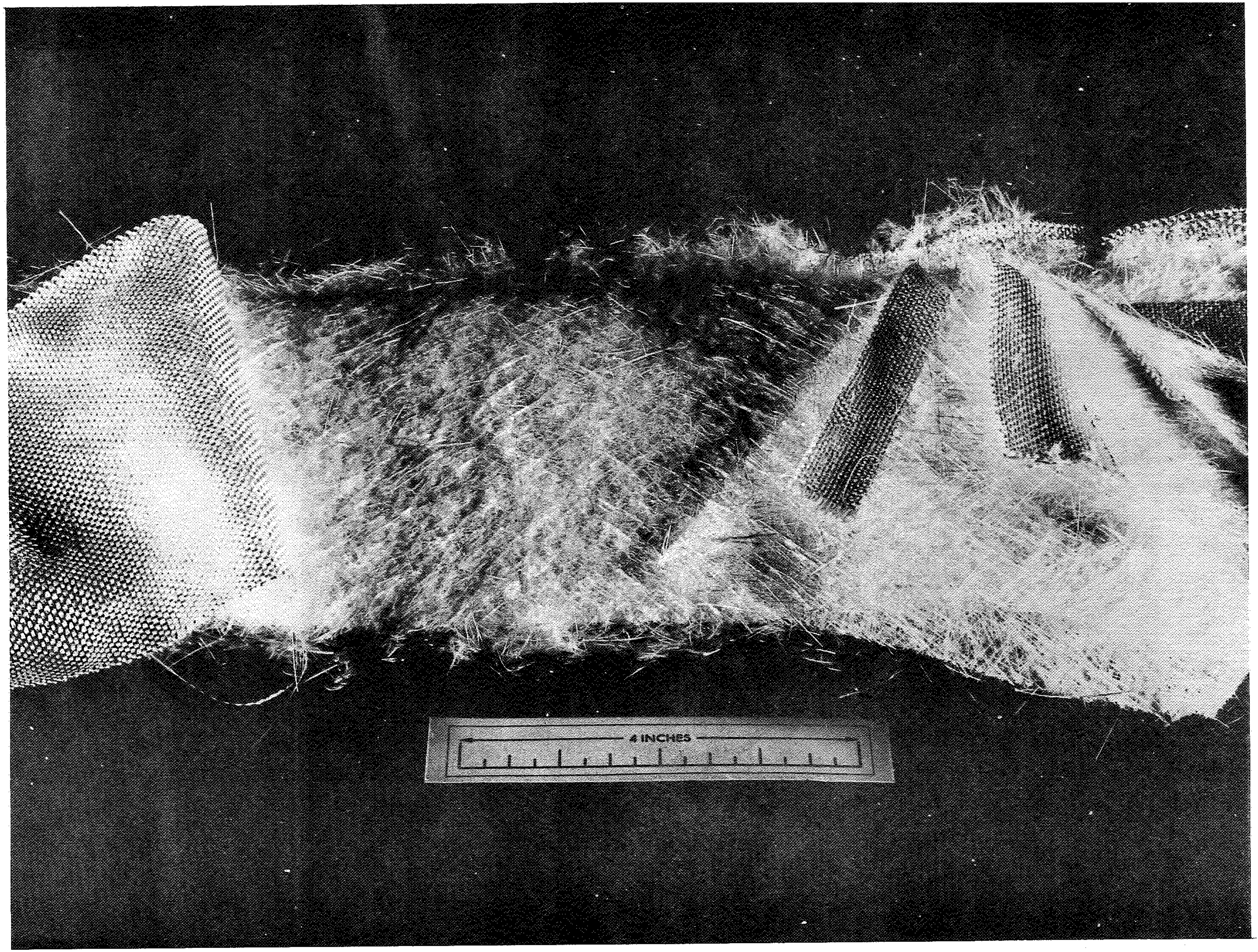


Figure 2 PHOTO TOP VIEW, NEEDLED FABRIC FROM H. SIMMONS

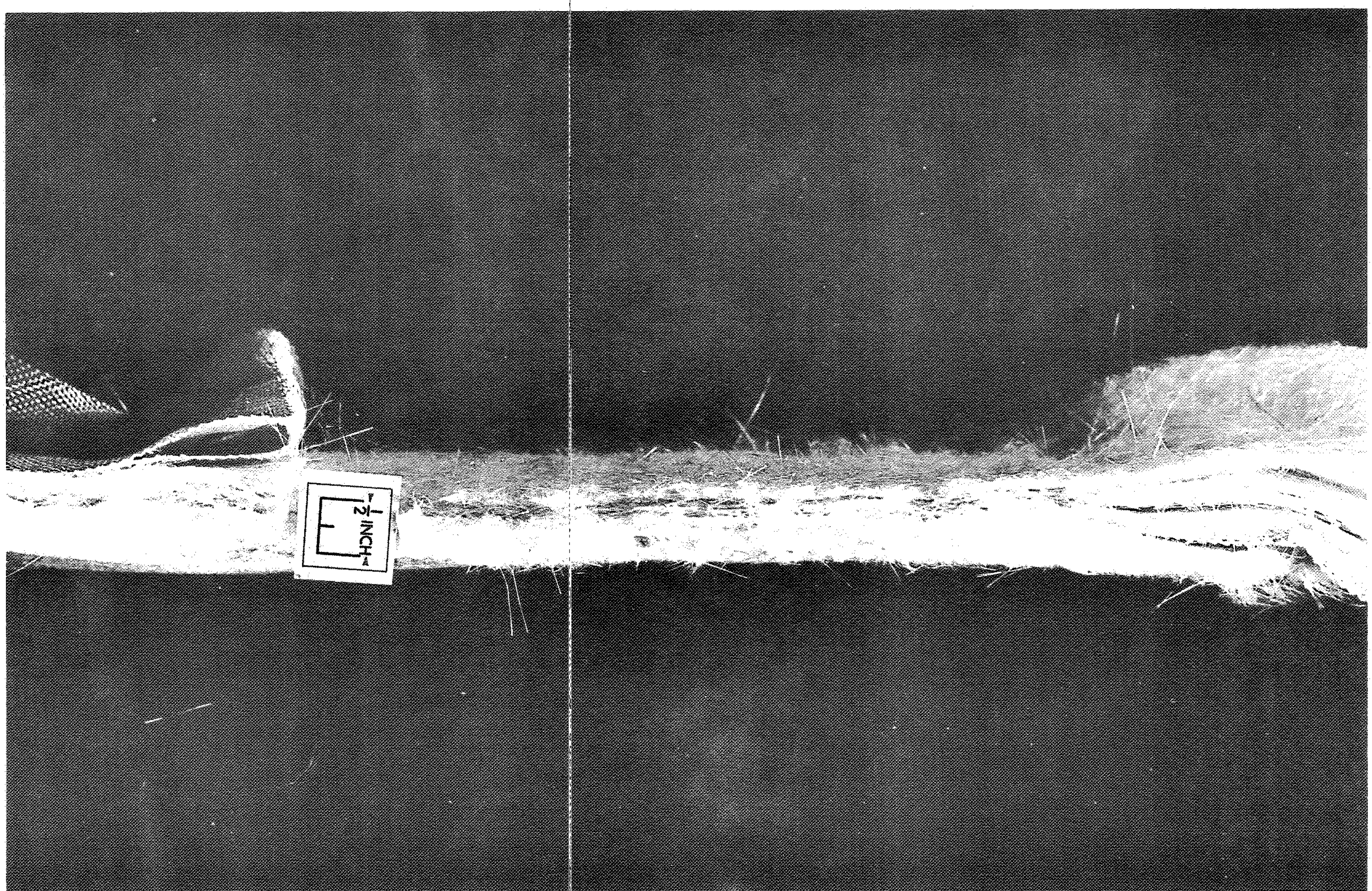


Figure 28 PHOTO SIDE VIEW, NEEDLED FABRIC FROM H. SIMMONS

b. Potential

The needling process is probably the most flexible technique studied in this investigation. The amount of interlaminar reinforcement can be changed from a very small amount ($\approx$ 1-percent fibers in the Z direction) up to a rather large but indetermined value. The penetrations per square inch range from 40 to 175 in the samples tested in this report, and the high range can be extended with only minor modifications. There appears to be an unlimited height of fabric that can be needled, though such a fabric would have to be needled in successive layers since maximum penetration of needles on any pass is about 1 to 1-1/2 inches and more generally in the region of 3/4 inch. Needling can be done on flat surfaces (the usual case), cylinders, cones, and surfaces of revolution. For some of these shapes fairly major modifications to the frame of the needling machine would have to be made, but there would be no question of whether the modified machine would work. A combination needling and tape wrapping could be done if specific orientation of the cloth were desired. Variations in cloth weave or the use of matt would also work. In fact almost any combination of weave, material, fabric orientation, and interlaminar reinforcement concentration would be attainable.

The disadvantage of this method is primarily involved with strength obtained through its use. The needling method is primarily a destructive method since the barbed needles used in changing some of the X, Y plane fibers into the Z direction do so by breaking the fibers and then pushing the ends perpendicular to their initial plane. If a matt or other non-woven fabric is used the change in the X,Y physical properties is relatively gradual as the number of needle strokes per unit area is increased. If a woven fabric is used, however, then the in-plane physical properties begin to drop quite drastically after relatively little needling. Thus if a high concentration of Z-direction reinforcement is required, the physical properties drop more than can be accounted for by a shifting of a percentage of the reinforcement from the X, Y plane to the Z direction, as is the case for all other techniques studied. Since this destructive mode of operation is the basis for the technique, elimination of this tearing would eliminate any Z-direction reinforcement, and attempts to place blind yarns across the laminations would be changing to another technique (sewing or tufting) rather than modification.

In summary, the needling technique is inherently very versatile and flexible but suffers because of its destructiveness to the in-plane (X, Y) strength at high levels of Z-direction reinforcement.

9. Avco 3-D

a. Avco Cartesian Coordinate Loom and Fabric

Avco SSD has developed a loom capable of producing a fabric containing straight, non-interlaced, continuous yarns in three orthogonal directions. This construction should optimize interlaminar strength of the composite since straight yarns under pure tension are the reinforcement in any of these three given directions, Reinforcement density and stiffness in each direction can be varied independently by varying yarn size, density, or material composition. Additional reinforcement is also possible in the 45-degree directions of the X, Y plane. Fabric densities as high as 2000 yarns per square inch in any, or all, of the three directions are possible.

The attainment of these aforementioned capabilities has been possible through a technical progression occurring from the basic, initial Avco loom being modified, improved, re-modified, etc., until the present loom has evolved, which represents an incorporation of many technical advancements into one machine. For this reason, it is felt worthwhile to trace the evolution of the present equipment, pointing out, where applicable, the more important modifications which have been responsible for the present state of the art.

The first loom built is shown in Figure 29. The sketches illustrated in Figures 30 through31 show schematically the sequence of operation for this loom. A short glossary is inserted at the end of this section, containing textile terms that may be unfamiliar to the reader.

In Figure 30, Plate B has just completed a traverse from west to east, causing yarns to be laid between each row of vertical tubes, as well as one yarn on the outside of each exterior row.

In Figure 31, plate C has completed a traverse from south to north, causing yarn to be laid in a similar pattern, but on top of, and perpendicular to, the previous layer in the same plane. Plate A is attached to a lowering mechanism synchronized in its downward motion with the build-up of yarn thickness due to these plates traversing.

Figure 32 shows plate B having completed its second traverse moving from east to west so that it has returned to its original position. It will be noted that an interlocking has taken place at the edge of the fabric between the outside yarn of one layer and the perpendicular yarns of the other layer. It will also be noted that yarns have been manually drawn through the vertical tubes.

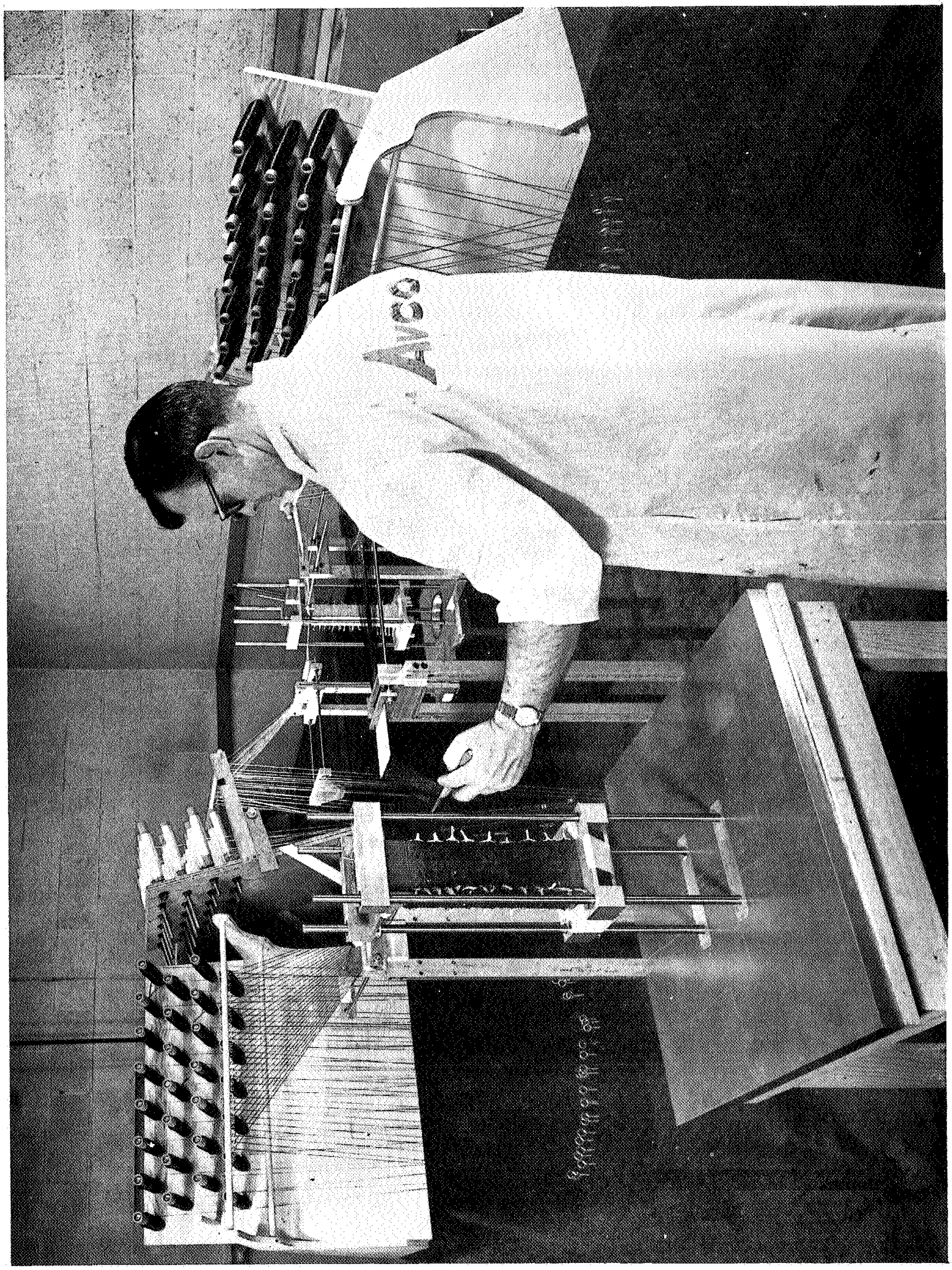


Figure 29 ORIGINAL AVCO LOOM

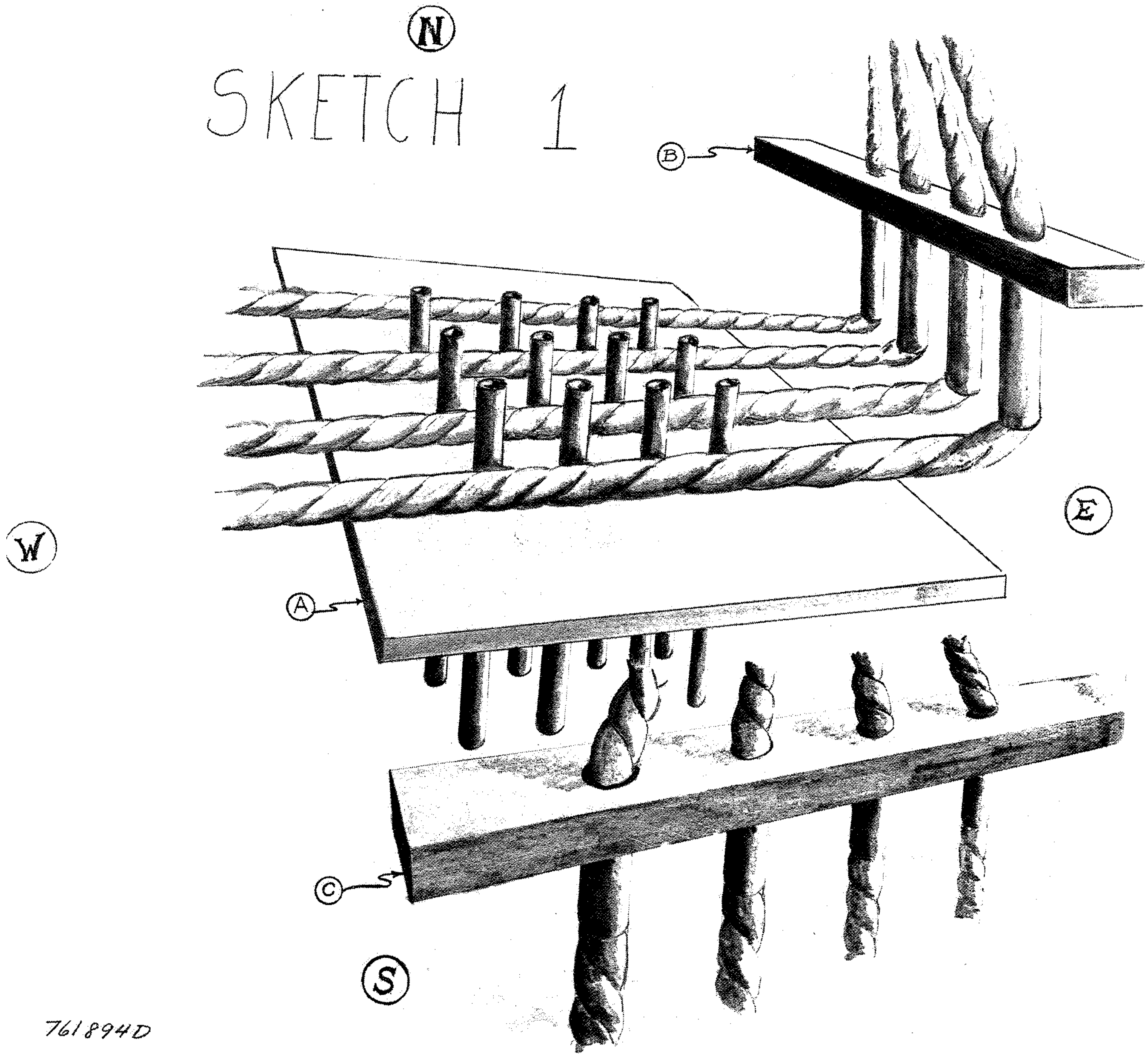
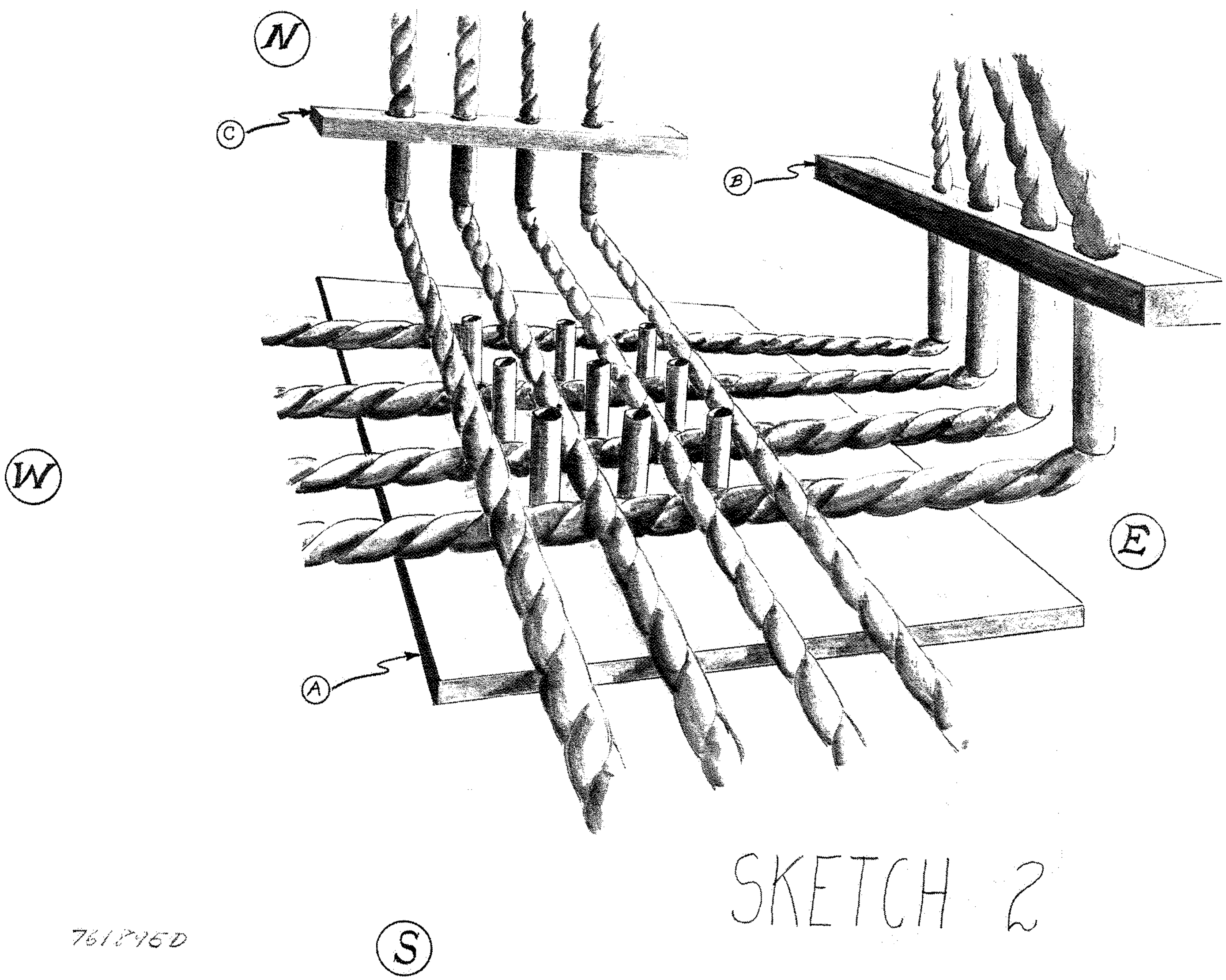


Figure 30 INITIAL HORIZONTAL YARN INSERTION



Fi g re 31 SECOND LAYER OF HORIZONTAL YA NS

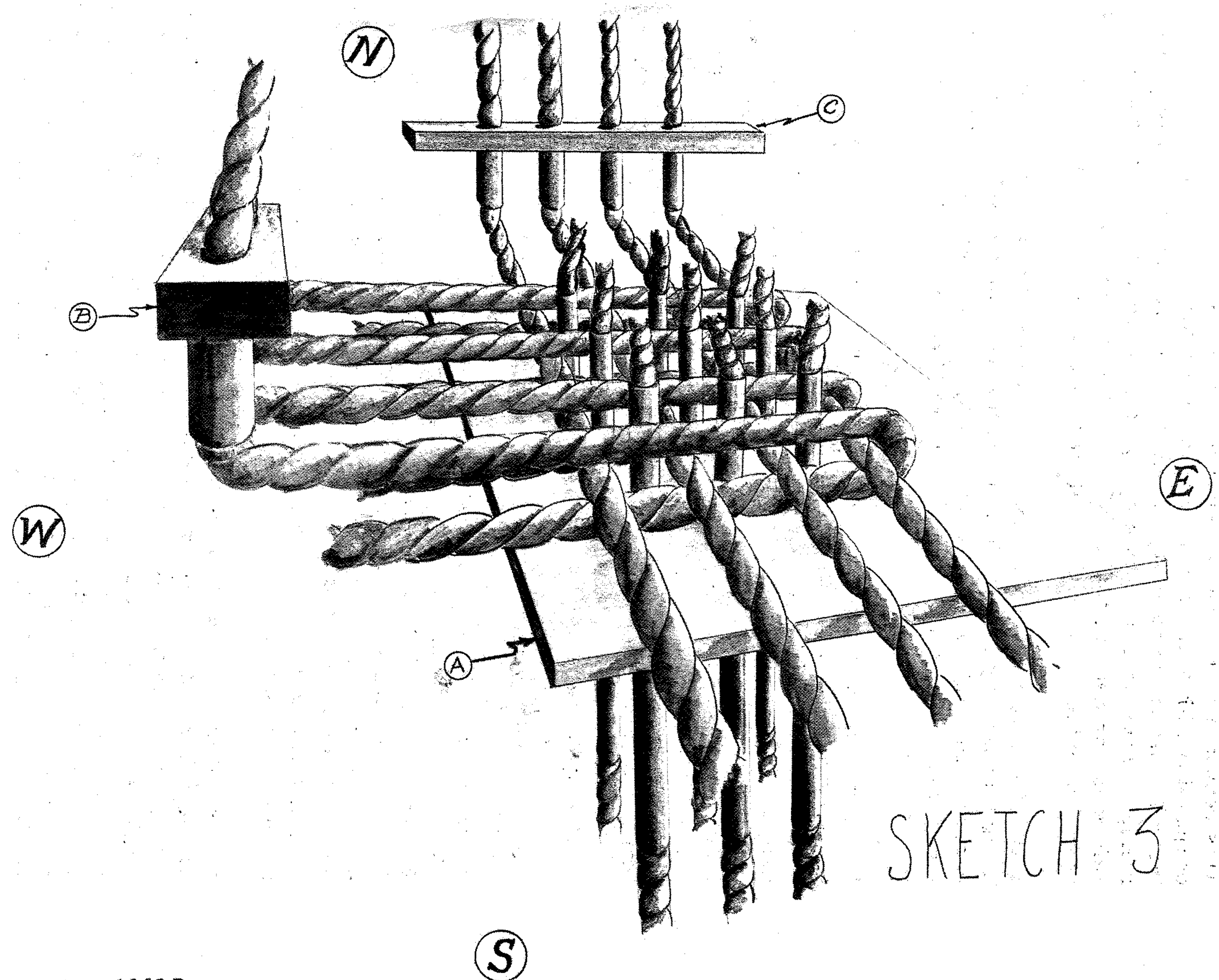


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Figure 3c THIRD LAYER OF HORIZONTAL YARNS

This sequence of alternating motions of plates B and C continues in conjunction with a synchronized downward movement of plate **A.** Since the initial layers of yarn are attached to plate **A,** this causes the woven fabric to move downward with this plate, to present a constant plane of reference for weaving to take place. This plane or position of the cloth is known as the "fell" of the cloth in conventional weaving terminology.

It was found that a sample height restriction of 2 inches was imposed using this technique due to bending of the long vertical tubes as their unsupported length increased during weaving, preventing the feed tubes from passing between them. This necessitated the modification shown in Figure **33.**

Using two plates to hold the vertical tubes between them, and inserting the horizontal yarns by the use of horizontal tubing instead of vertical tubing, this height limitation has been overcome. Fabrics 12 inches in height have been recently woven on this loom. Figure **34** shows a sample 6-1/2 by 6-1/2 by 8-1/2 inches high. Figure *35* shows the part after removal from the loom, with the vertical yarns drawn through. Figure *36* shows the compressing tools used to attain the desired fabric density prior to insertion of the vertical yarns. Figure 37 shows a magnified view of the woven fabric part. It can be seen that the original height of 6 inches of fabric prior to vertical yarn insertion was compacted to slightly less than half of this height (in Figure 35). It is extremely important to attain a well-compressed part prior to impregnation and molding, since further compaction of the part during these operations would tend to cause disarrangement of the vertical yarns so that they would no longer be straight. This might considerably decrease the effectiveness of these yarns in sustaining a load imposed on them. Figures **38** through 40 show the sequence of operation for this loom. The sketches are self explanatory, with only two basic differences in operation from the original loom. **As** previously pointed out, feed tubes are horizontal instead of vertical, and external selvage yarns are inserted manually. All of the samples prepared for this contract were made using this loom.

It was felt that an even more homogeneous reinforcement could be attained than that produced using this loom. The spacing of the vertical tubes, as well as the diameter of the tubes could be diminished. This would effect a closer packing of yarns in all directions, with a concomitant reduction of unreinforced resin area. The spacing of the tubes (or vertical yarns) on the samples prepared for this contract are shown in Figure 41. The spacing of vertical yarns produced on a loom now under development is shown in Figure 42. The loom that produces this arrangement is shown in Figure 43. The tapered shape of the vertical tube pattern is necessitated by the inherently larger tube spacing

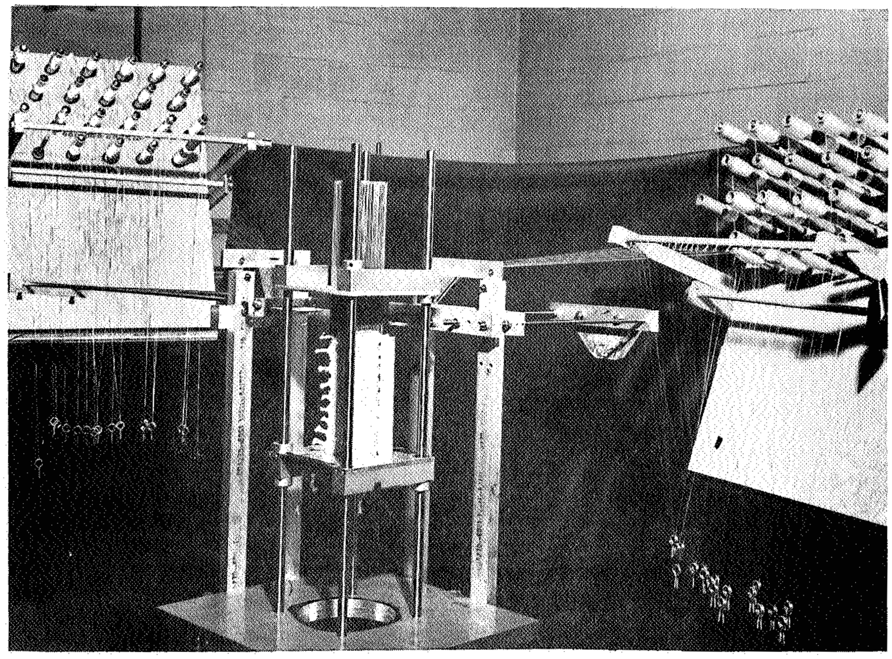

Figure 33 MODIFIED AVCO LOOM

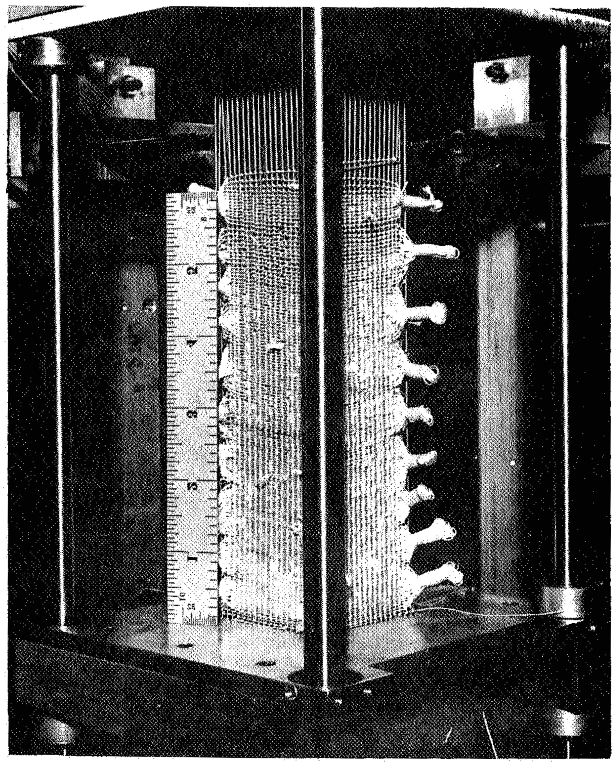

Figure 34 CLOSE-UP OF WOVEN FABRIC ON AVCO LOOM

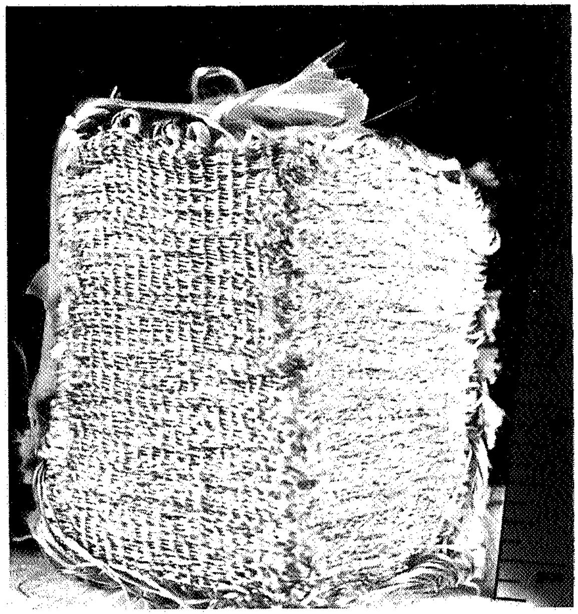

Figure 35 AVCO 3-D FABRIC

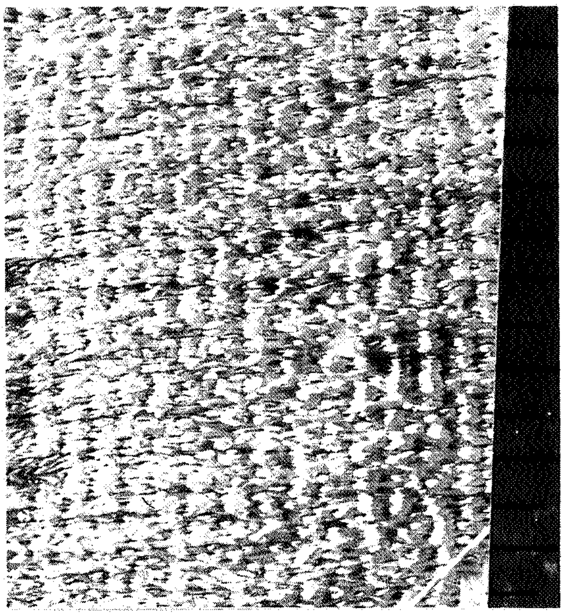

Figure 37 MAGNIFIED CROSS-SECTION OF AVCO 3-D FABRIC

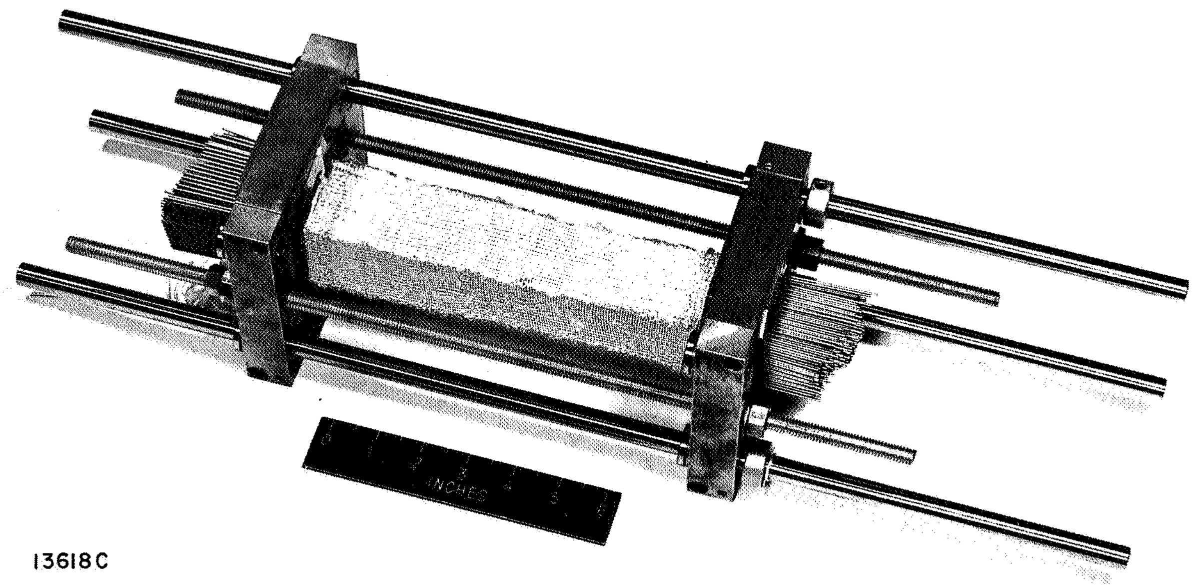

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Figure 36 FABRIC COMPRESSION SETUP

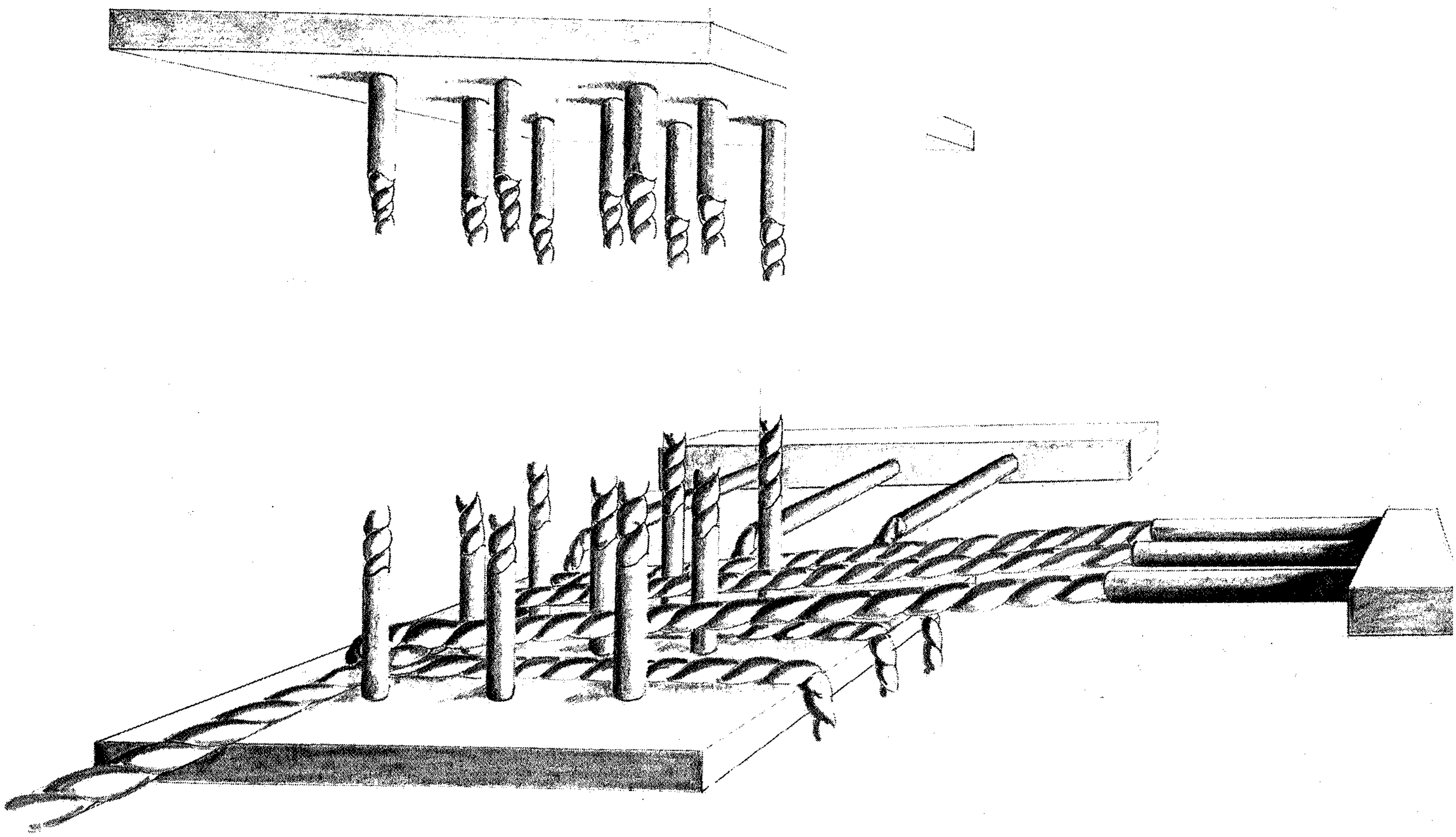

Figure 38 FIRST DOUBLE LAYER OF YARNS

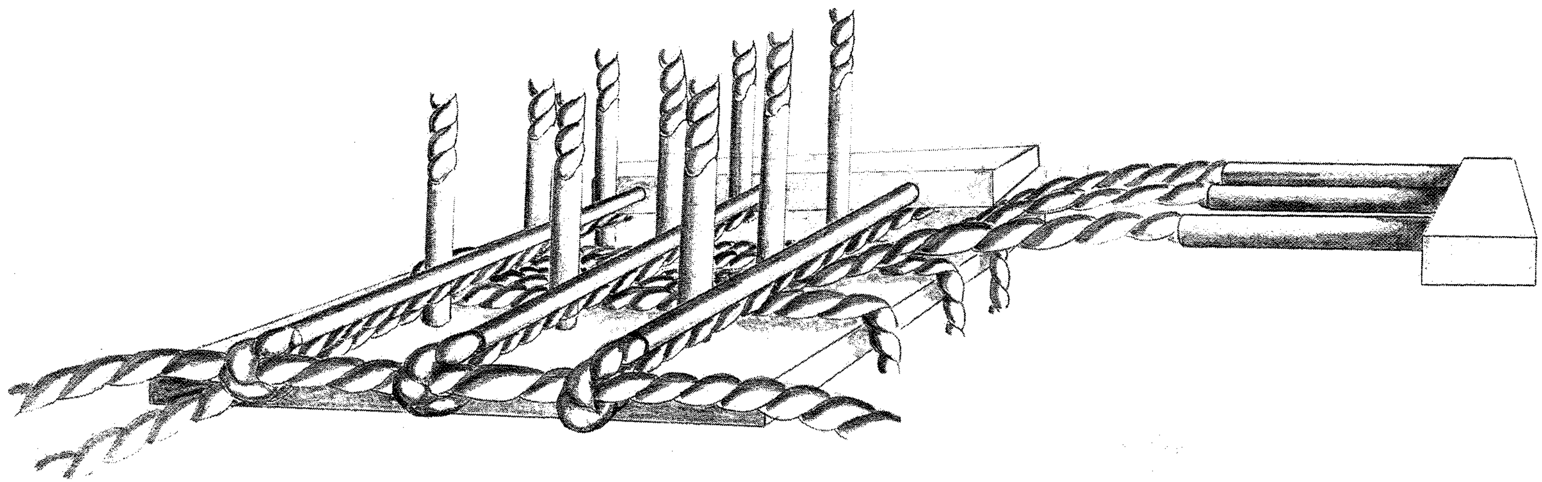

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Figure 39 SECOND DOUBLE LAYER OF YARNS

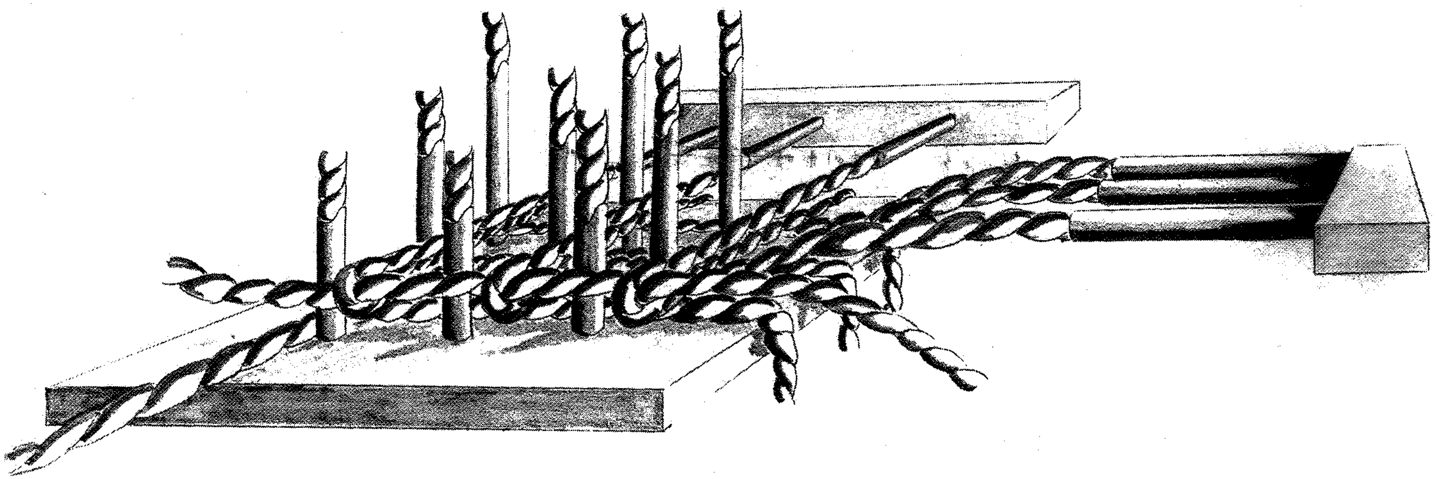

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Figure 40 COMPLETION OF ONE SEQUENCE

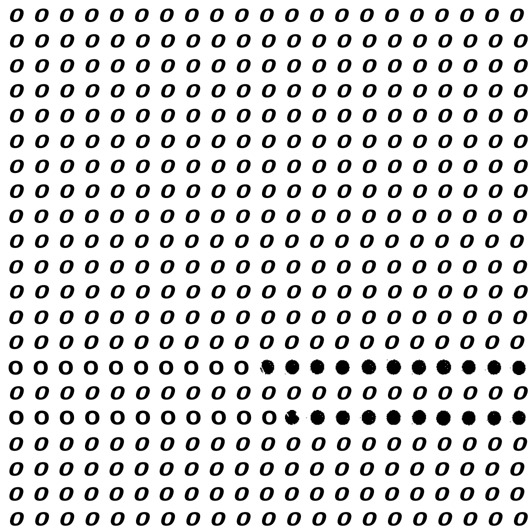

Figure 41 STANDARD Z ARRAY

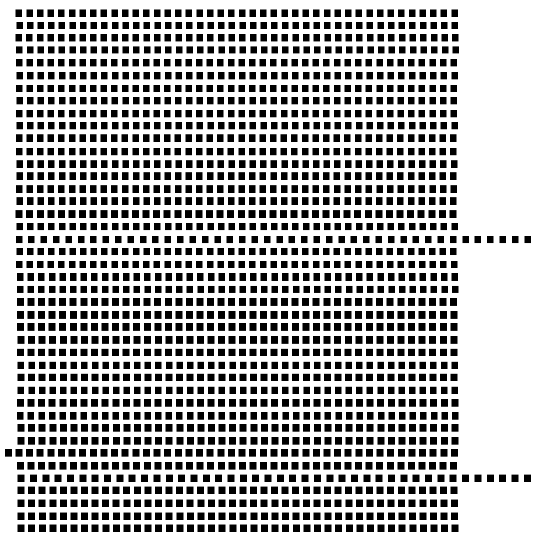

Figure 42 FINE DISTRIBUTION Z ARRAY

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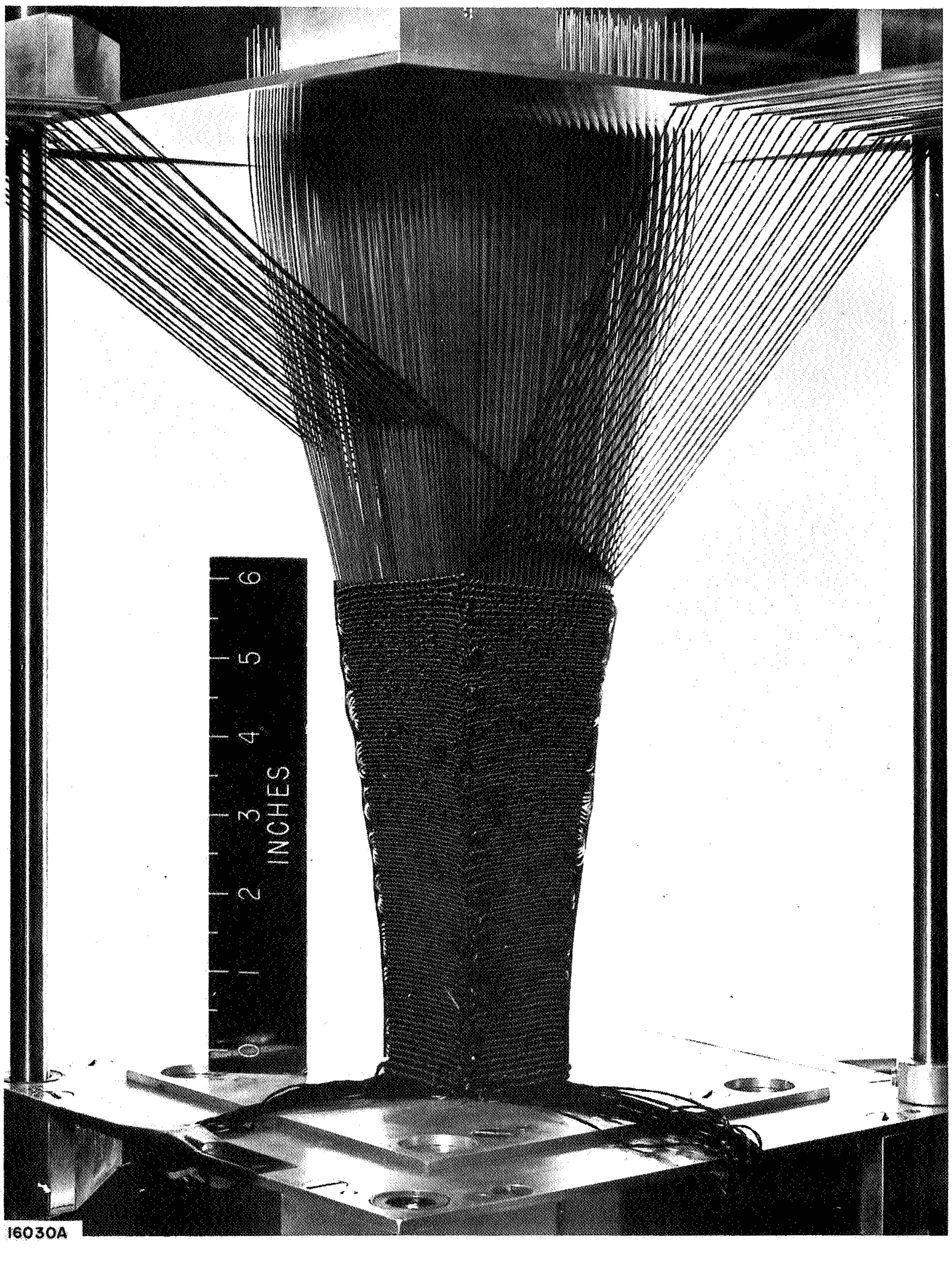

Figure 43 FINE DISTRIBUTION LOOM

required at the top, for horizontal yarn insertion, while maintaining the desired closer tube spacing at the bottom. The spacing at the bottom is the spacing ultimately achieved in the sample.

This spacing is still not ideal, however. Ideally, one would desire that each horizontal yarn he separated only by a distance required to insert a single vertical yarn. To accomplish this ideal, still another modification is being planned.

The vertical tubes are eliminated completely and replaced by yarns of equal diameter. The two plates that held the tubes in alinement are replaced by devices known in the textile industry as "expanding neck reeds." A normal reed is a device used in standard weaving to beat up the pick into the fell of the cloth after the pick has been inserted into the shed by the shuttle. A non-adjustable reed contains a given number of equally spaced, vertical metallic strips attached to a frame. The spaces between these strips are known as "dents," through which the warp yarns are drawn for proper spacing and control during weaving. The specific reeds under discussion here are adjustable, so that the spacing between dents (or yarns) can be adjusted to any desired distance. If one of these reeds is placed above, and at right angles to, a second reed, their respective intersecting dents form small rectangles through which yarns can be drawn. If, for example, 20 rows of 20 yarns each are drawn through a set of these reeds and then through a second similar set of reeds in the same sequence, and the two sets of reeds properly alined, a solid rectangle of regularly spaced yarns is formed. A variety of yarn patterns can now be attained by turning any of the four adjusting wheels on the reeds.

Now assume we wish to weave a fabric using yarns of 0.025-inch diameter in three directions in the fabric. We adjust the bottom set of reeds to provide a vertical yarn spacing of about 0.020 inch. Since a larger spacing than this is required if a horizontal yarn is to be placed between them, the top set of reeds is adjusted to provide this larger spacing (possible 0.050 to 0. 100 inch). The top set of reeds is positioned a suitable distance above the bottom set of reeds and is adjusted to provide a larger spacing (in two directions) between the yarn ends passing through it to provide adequate space for horizontal yarn insertion. (See Figure 44.)

Two sets of horizontal carriers are used to insert the horizontal yarns into the fabric and present a loop at the opposite selvage. A selvage yarn is placed through these loops and the needles are retracted, leaving double picks inserted. Alternating motions of the horizontal needles in the two perpendicular directions take place. The sequence of operation is the same as in Figures 38 through 40,

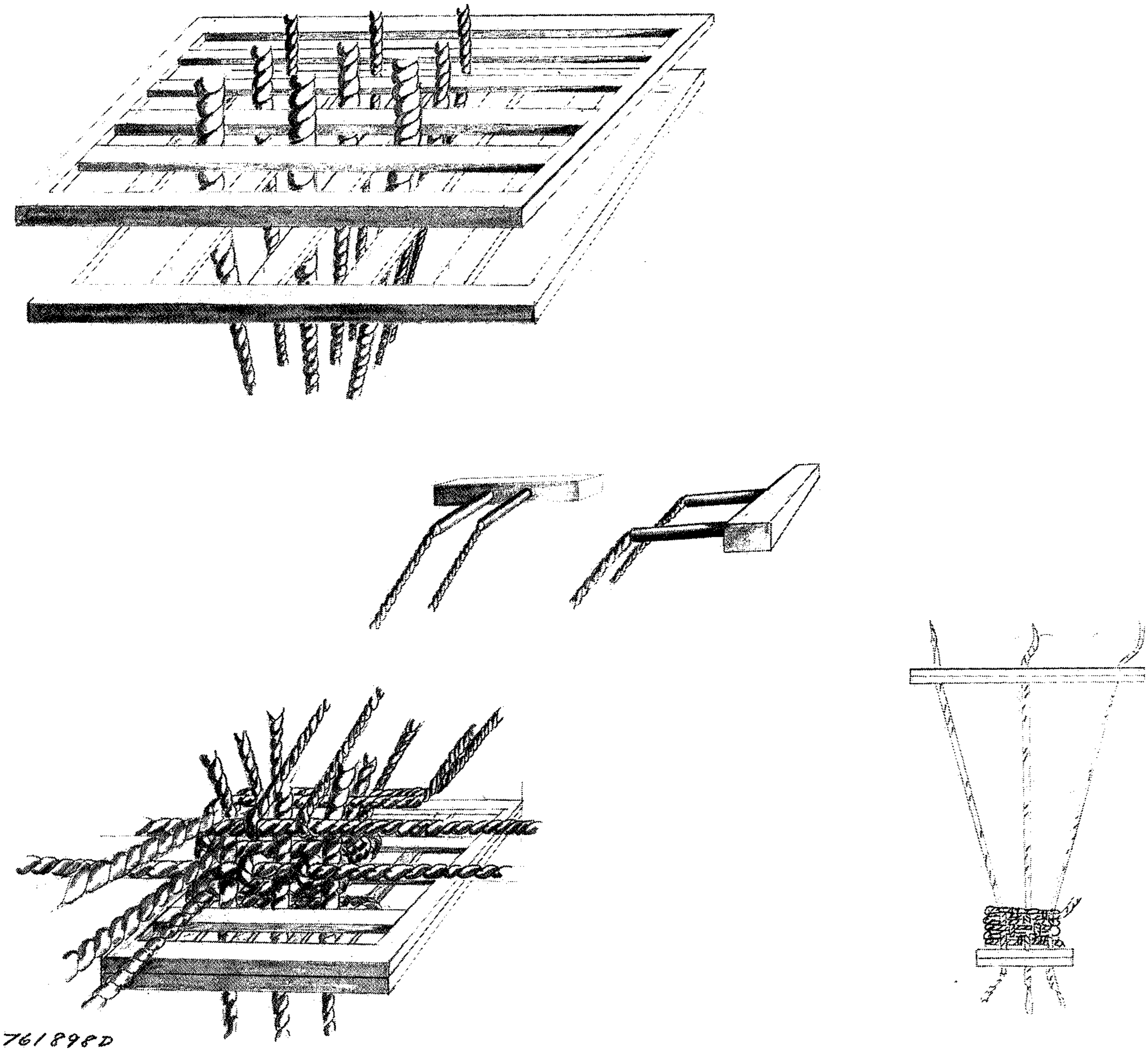

Figure 44 EXPANDING NECK REED LOOM

The tension on the horizontal yarns after the selvage is inserted causes the vertical yarns at the fell of the cloth to attain the width dictated by the bottom set of reeds, This follows the same technique of standard weaving practice, The horizontal yarns can be beaten down toward the bottom set of reeds by another rigid reed, assuring good downward compaction. The fabric attains the ultimate condition that all yarns are under compression from their neighbors, As the fabric is gradually built up, the bottom reeds to which the bottom ends of the vertical yarns are attached move downward, drawing new yarn through the top set of reeds The last pick beaten down represents the fell of the cloth and continually presents a controlled tight spacing of vertical yarns into which succeeding picks are downwardly forced.

A major advantage of this concept is that the vertical yarn spacing is adjustable. This is extremely helpful in attaining the exact spacing necessary both for inserting the picks at the top reeds and to provide the tight spacing necessary at the bottom reeds for good yarn packing and inter-yarn friction. In addition, a complete fabric is woven in one operation With the current method, it is necessary to insert vertical yarns through the fabric manually after horizontal weaving has been completed. This is a tedious and time-consuming task, usually requiring as many man-hours as is used in weaving the basic horizontal yarn structure. In addition, adjustments of the machine can be made easily for different yarn diameters.

The major long-range advantage of this concept is that it should lend itself quite readily to scale-up, using existing loom manufacturing technology. One can envision, for instance, that the "vertical" yarns can become horizontal, simulating standard warp yarns. The operation can now become continuous and automatic, all yarns being fed continuously from creels. This type of weaving is known in the industry as "narrow-fabric" weaving and may be done on a "needle loom." These looms use flat needles, instead of shuttles, to transfer the picks through the shed.

The picks are interlocked on the far side of the fabric by knitting needles which automatically form a knitted selvage. A multitude of warp yarn layers and a multitude of needles would be used in this case, with stationary "sheds" or openings between yarn layers, instead of oscillating layers as on standard weaving.

b, <u>Avco Knitting Mechanism Cylindrical Coordinate Loom</u>

A further projection of this basic concept is the loom under development by Avco for cylindrical parts.

The key to the feasibility of this operation lies in the utilization of a commercially produced knitting needle. This needle and its operation are shown in Figure 45. This latch needle is provided with a hook to hold the newly formed loop of yarn. It also has an area for retaining a loop or several loops of previously knitted yarn. The latch is a bar, pivoted on one end, so that it can cover or close the hook, This allows the newly formed loop on the hook to be drawn through a previously formed loop. The latch in its opposite or open position permits the loop or loops caught by the hook to move into the secondary or retaining area. The actual loops of yarn cause the latch to change position.

In the first step in Figure 45, yarn has just been fed into the hook portion, while a previously formed loop is shown in the retaining position. This old loop is held in a stationary position laterally by means not shown here, so that the needle can move transversely within it without any transverse motion of this loop occurring. Step 2 indicates the needle moving toward the right, so that the old loop causes the latch to close the hook. Steps 3 and 4 show the continued motion of the needle to the right, causing the old loop to pass over the end of the needle (called "casting-off") and to be held by the newly formed loop.

Step 5 shows the needle reversing its direction and moving toward the left, causing the latch to open so that new yarn can be fed to the hook. Step 6 shows the needle back to its position in Step 1, ready for acceptance of new yarn into the hook.

Figure 46 illustrates a sectional top view of the existing circular loom bed.

Another plate is being made with grooves cut radially into its surface so that latch needles of the type just described can fit into these slots. (See Figure 47.) The slots are so positioned that they coincide with the spaces between the radial rows of tubes on the existing loom plate. If the needles can now be caused to move toward the center of the loom so that they pass between tube rows, subsequently have yarn fed onto their hooks, and then retract to a position outside the tube pattern, radial yarns will then have been placed between the radial rows of tubes.

The other end of the knitting needle contains a cam or "butt" that protrudes perpendicular to the shank. By pushing on this cam parallel to the needle shank, the needle can be caused to move within its slot in a radial direction relative to the center of the needle plate. A circular plate with a groove cut circumferentially as shown in Figure 48 is made to accept the needle butts. This plate is placed groove down on top of the slotted needle bed so that the needles are held secure in their slots and the needle butts are positioned within the milled circumferential groove.

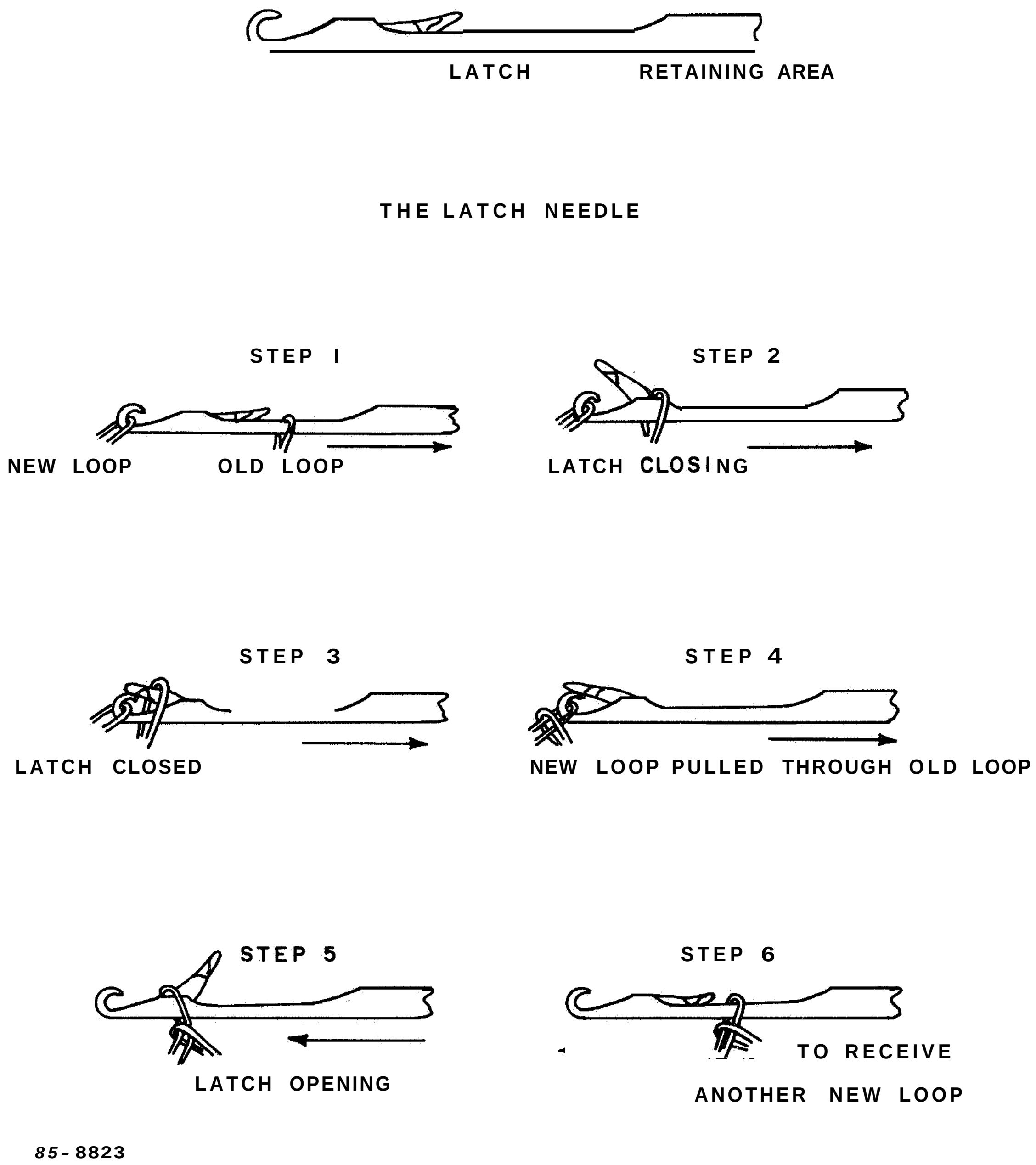

Figure 45 THE KNITTING CYCLE

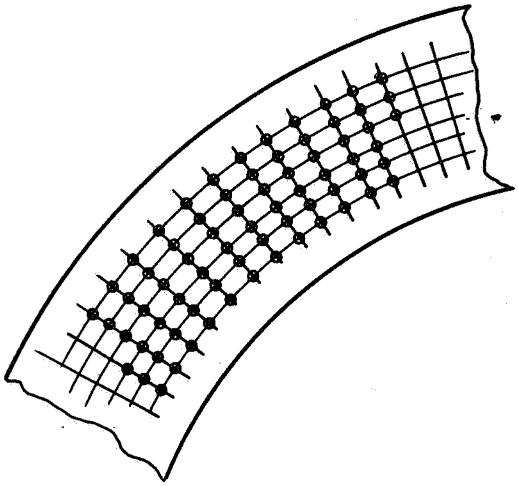

Figure 46 SECTIONAL TOP VIEW OF CIRCULAR LOOM BED

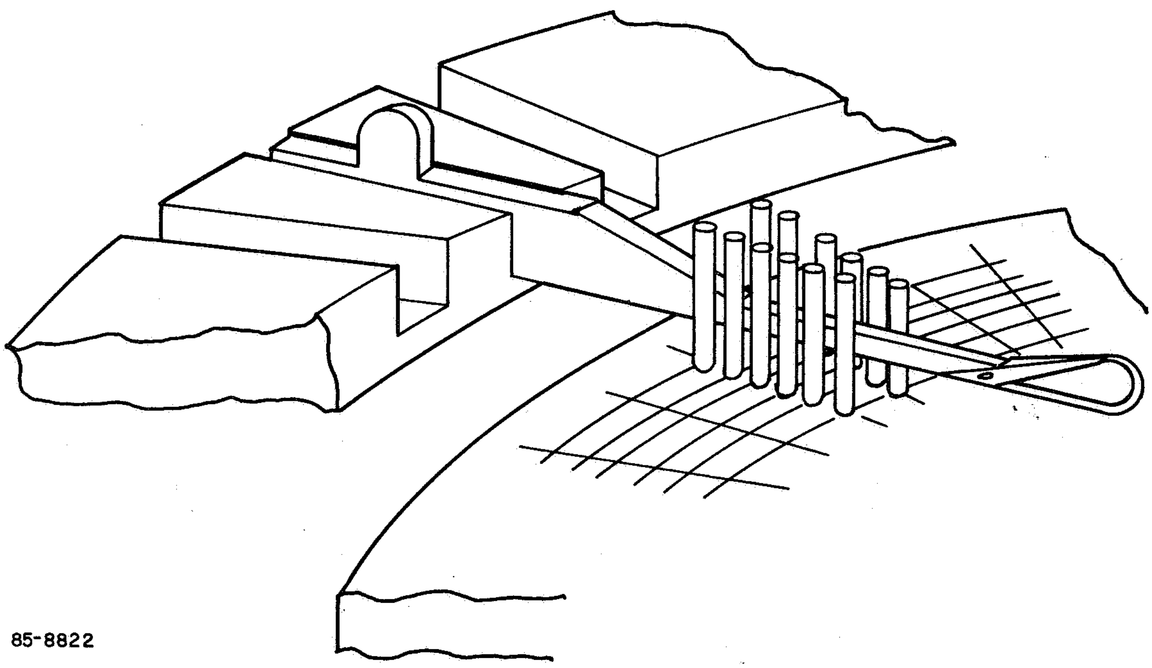

Figure 47 SECTIONAL VIEW OF NEEDLE HOLDER PLATE

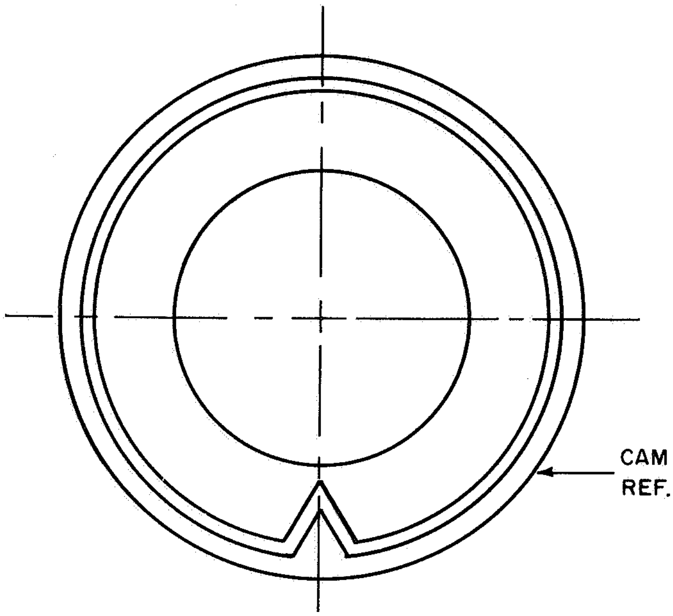

Figure 48 CAM PLATE FOR CIRCULAR LOOM

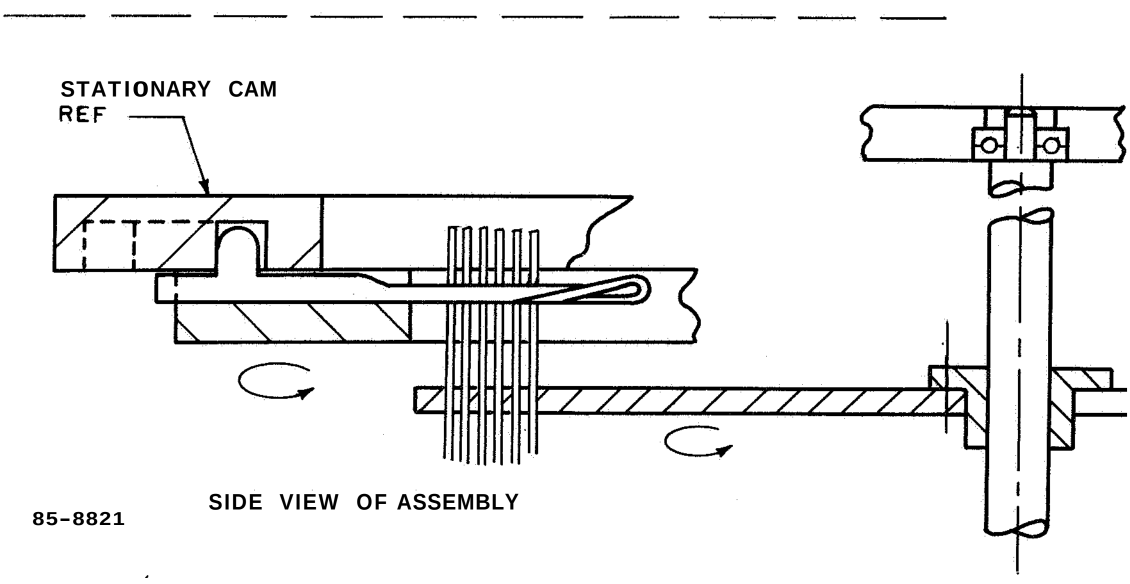

Figure 49 SIDE VIEW OF ASSEMBLY

The needle bed and tube loom plate are now attached to a common shaft about which they can rotate. The grooved plate is held down on top of the needle bed and held stationary while the needle bed and loom plate are caused to rotate simultaneously, being keyed to the same shaft. (See Figure 49.) This motion causes the needles to follow the path of the groove which their cams are riding. A given needle will ride in this circumferential groove, in which position the needle hook is held just outside the tube pattern, until its butt reaches the V groove. This V groove will cause the needle to gradually move radially between two given rows of tubes until its hook protrudes on the inside of the tube pattern. Yarn is fed to the hook at this point, and the needle is then gradually retracted under the reverse action of the V groove. Twelve needles will actually be in some degree of inward or outward motion at any given time. (See Figure 50.)

In addition to radial yarn insertion, there is the requirement that circumferential yarns be inserted in alternate layers with the radial yarn layers. A stationary set of feed tubes (Figure 51) is positioned such that these tubes protrude in between circumferential rows of loom tubes. Once the ends of yarns drawn through these feed tubes are attached to the loom plate, the rotation of the loom plate will cause yarn to be continuously drawn through these feed tubes and to be laid circumferentially between the loom tubes, The needles are in a retracted position (outside the loom tube circle) when they reach the location of these feed tubes. Thus, a circumferential layer of yarn is laid on top of a previously inserted radial yarn layer.

A circumferential yarn is laid down on the outside of the tube pattern between the tubes and the needle hooks holding the radial loops. (See Figure 52.) A yarn guide just prior to the needle insertion area holds this outside circumferential yarn below the plane of the needle bed, This serves the function of holding the yarn loops down under tension on the needles so that these loops will not escape when the needle moves forward, but will be held on the retaining shanks of the needles, as intended. The knitting action which takes place on these needles is exactly as explained in the earlier part of this discussion. The outside fabric surface actually becomes a knitted structure.

A yarn guide on the inside of the needle bed (Figure 53) feeds yarn to the active needles due to the rotary motion of the needle bed. Among the more critical areas upon which the feasibility of this method depend are--

1) The effective feeding of the yarn to the needles.

2) Prevention of the escape of radial yarn loops from the needles at the initiation of needle insertion.

3) The relative severity of handling imposed on the yarn as the needles retract.

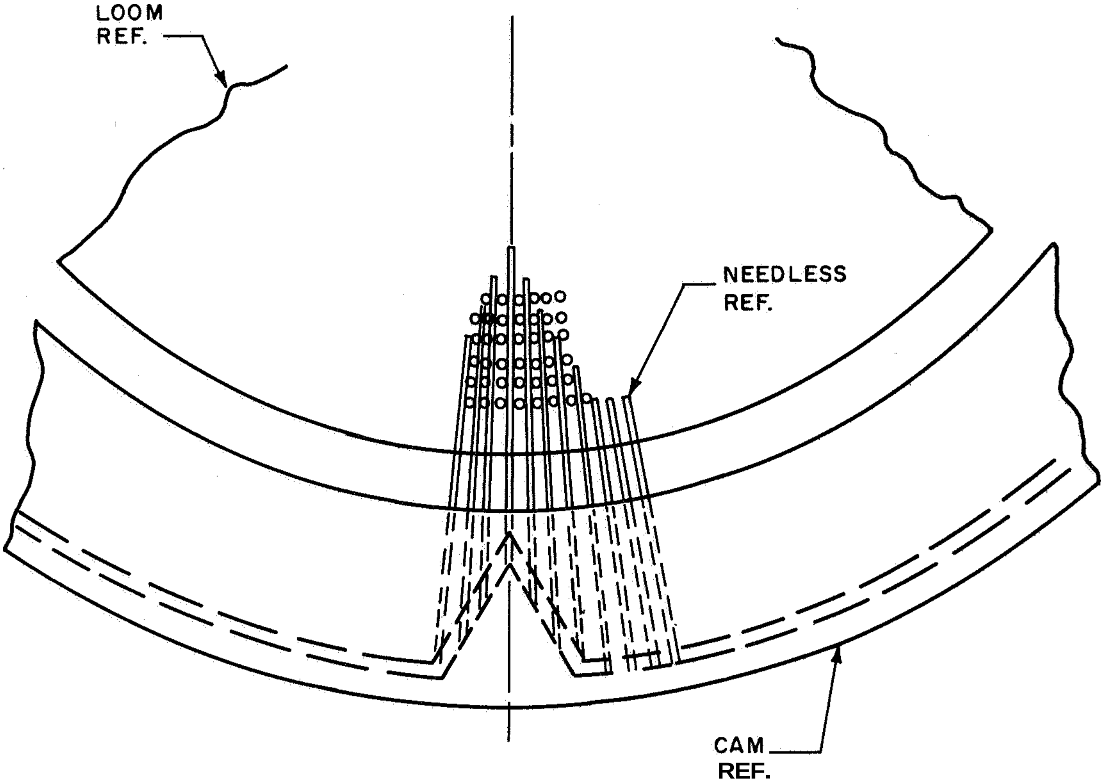

Figure 50 CAM OPERATION OF NEEDLES

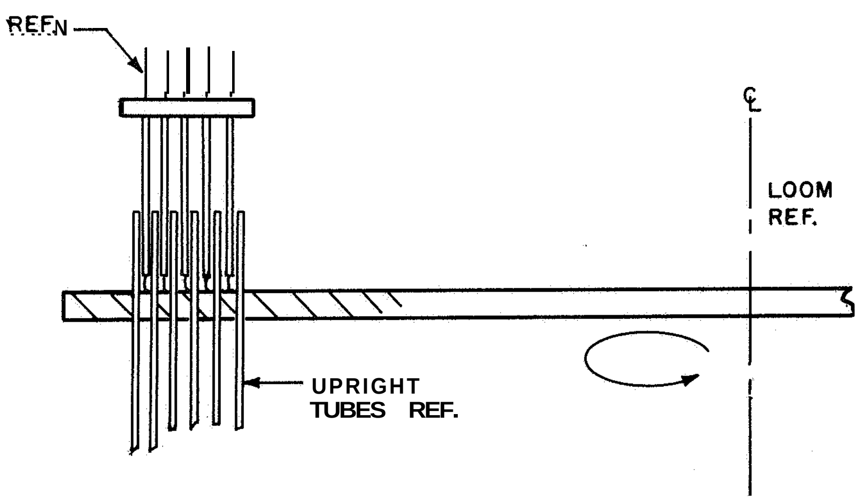

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Figure 51 CIRCUMFERENTIAL YARN FEED SETUP

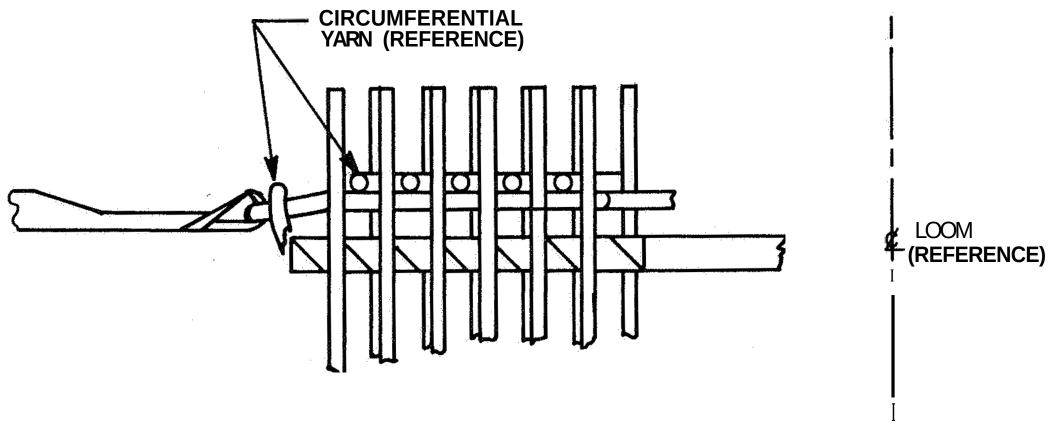

Figure 52 RADIAL YARN STABILIZATION TECHNIQUE

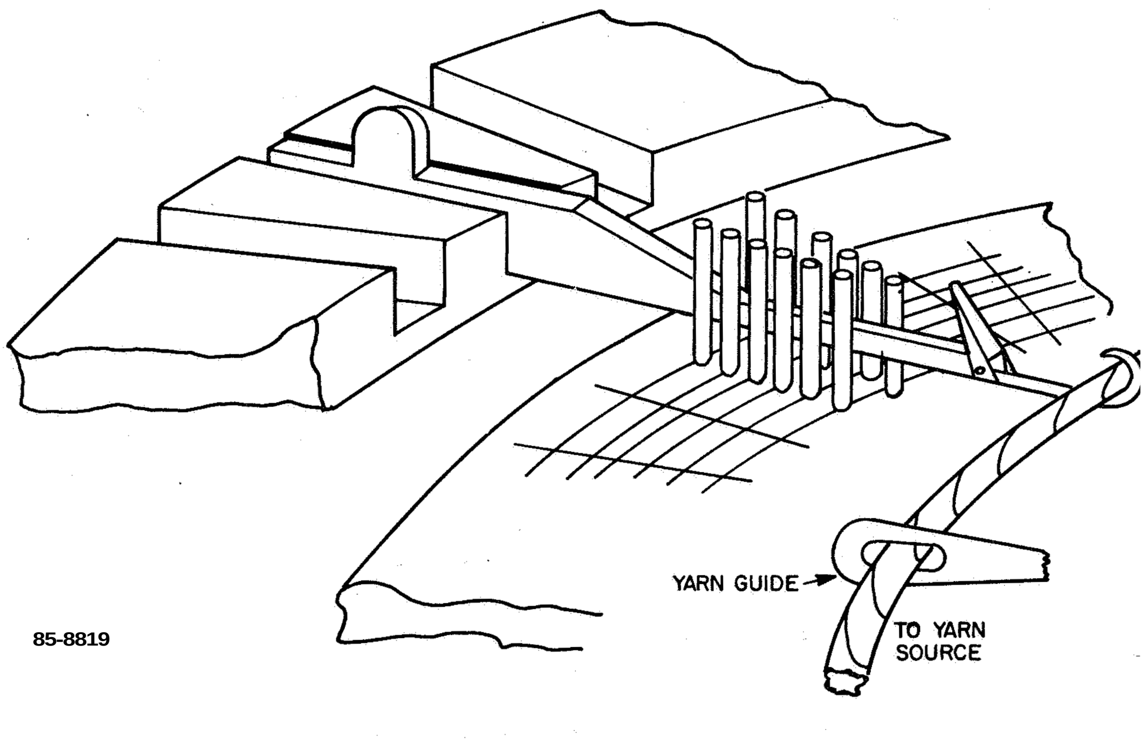

Figure 53 INITIAL STEP OF RADIAL YARN INSERTION

Figure 54 shows the loom in hand operation.

c. Avco Porcupine Cylindrical Coordinate Loom

There is a distinct second approach for the fabrication of 3-D cylindrical composites at Avco, which approach is also being converted into a laboratory manufacturing process. The objective of this approach is the same as the needle loom approach -- to have filaments oriented in the hoop, axial, and radial directions. A description of this approach is given below.

The 3-D mandrel shown (with a quarter section cut away) in Figure 55 was designed and built to arrange filaments, or prepreg tapes, of any flexible material in a predetermined, tri-directional arrangement with a degree of precision limited only by the dimensional accuracy of the filament material. It borrows some of the well established winding techniques in the industry and adds provisions for the insertion of radial elements. It is essentially an experimental piece of hardware intended only to check out the feasibility of the concept. For this reason, every effort has been made to utilize existing equipment, such as an engine lathe and a drill press. Also, operations which on a second generation machine would be mechanically actuated (i.e. , by cam) are, for present purposes, performed manually.

The mandrel consists of eight removable wedges maintained in a cylindrical array by bolting to two circular end flanges. The center line of rotation is established by two tri-legged spiders as shown in Figure 55 . Both the wedges and the spiders have machined shoulders indexing onto circular flanges to effect correct alinement. Any possible runout is eliminated by finish machining the O. D. of the wedges with the entire mandrel assembly supported on the spider centers. The peripheral shoulders of the end flanges are slotted to locate the correct number and size of axial elements. The segmented cylindrical surface is fitted with radial pins whose function is to prevent any stagger in the stack up of the circular elements during winding. The spacing and size both of the slots on the flanges and the pins on the cylinder are determined by the ratio of the different types and sizes of filament required for each specific sample, i. e. , the desired radial volumetric loading and, consequently, the size and lattice spacing of holes that must be left between the longitudinal and hoop windings. Whenever possible, these filaments should be grouped into prepreg tapes, each containing the correct number of individual strands to yield the desired ratio. This is very convenient for two obvious reasons:

1) It cuts down the number of turns on the mandrel for any given volume of material,

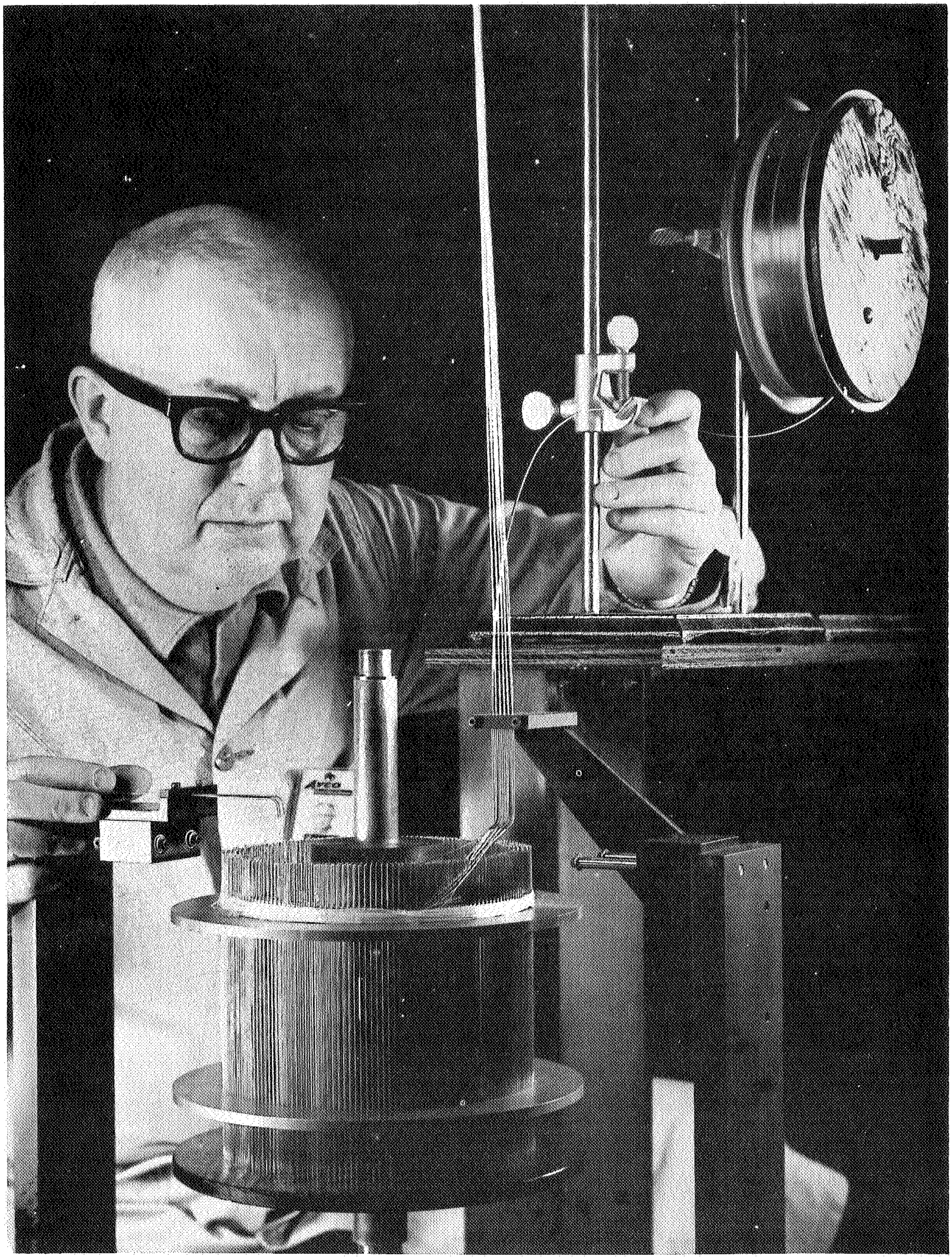

Figure 54 HAND OPERATION OF KNITTING CYLINDRICAL LOOM

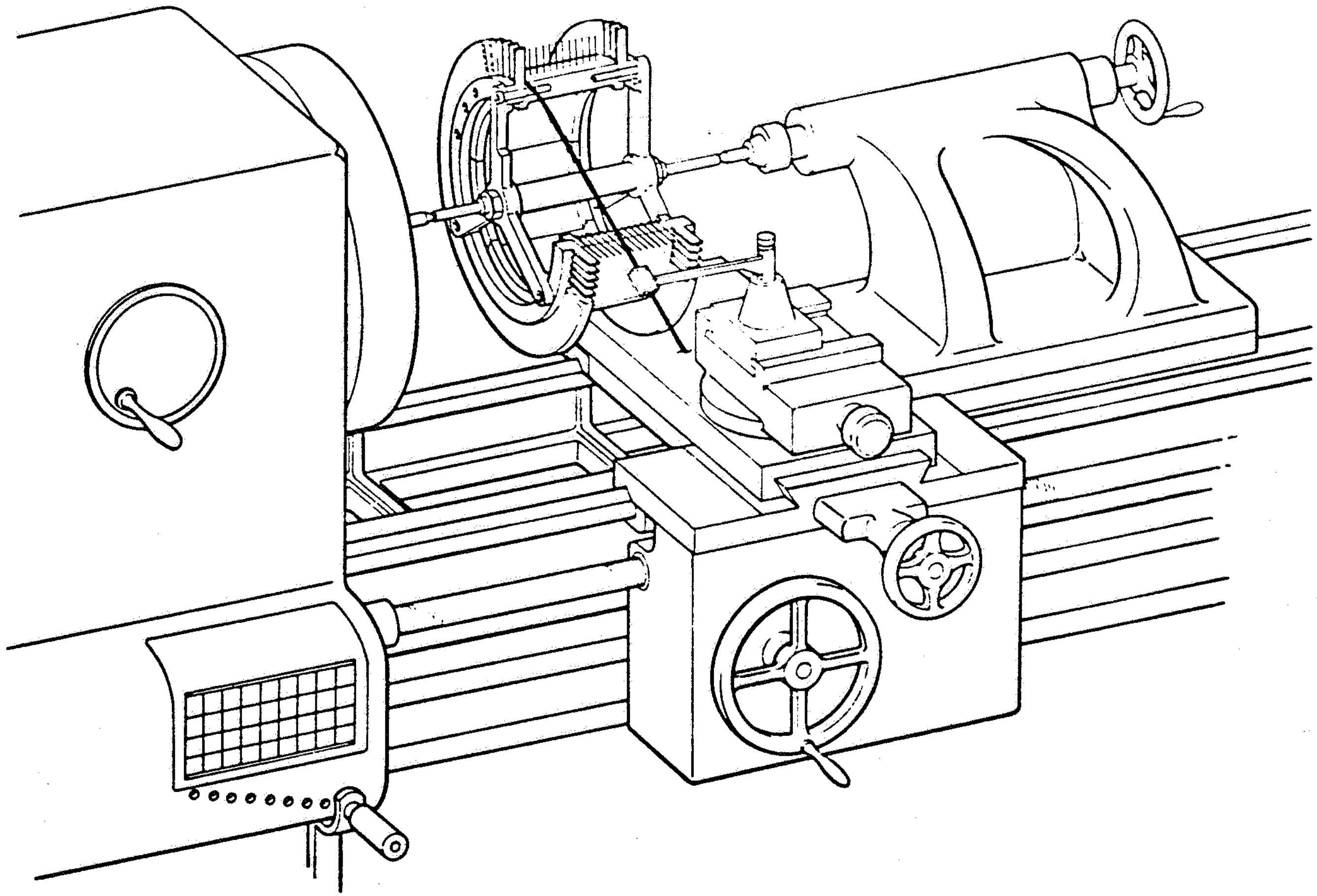

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Figure 55. PORCUPINE LOOM: LATHE SETUP FOR LAYING CIRCULAR AND HORIZONTAL ELEMENTS

2) It reduces the probability of stack-up stagger, i. e. , of having the hoop and axial filaments traveling laterally from their assigned positions and hence not leaving a clean hole for the insertion of the radial filaments.

Figure 56 shows the mandrel supported on a roller fixture allowing it to rotate about its own axis. The fixture is clamped on the work table of a standard vertical drill press so that the axis of the process spindle lies on a diametral plane of the mandrel, The needle assembly shown in Figure 57 is locked in the chuck of the drill press and can thus be lowered and raised on a precise reproducible location. The needles of Figure 57 are identical to those used in the needle loom approach, as shown in Figure 45.

At the end of the down stroke, the latch needles are threaded in the manner described in Step 7 of the next section, and the following raising motion will place yarn in all radial holes located in any given axial plane. This simultaneous insertion of radial elements is the distinguishing characteristic of the proposed system, It is relevant to point out that the principle can be applied to any length of cylinder by using a longer row of radial needles. Similarly, the longitudinal members can be cut and inserted in any length, without any great difficulty. For the circumferential filaments, one merely winds a longer cylinder.

The steps for sequential operation are described below:

1) With the mandrel supported on center the first layer of circular elements is wound. The winding will start from one of the pins closest to the flange. It will be clearly marked for this purpose so that it will become the starting point for all other successive circular layers. When the first layer has covered the entire surface, the end of the tape is cut and bonded onto the cylinder with an adhesive.

2) The first layer of longitudinal tapes is now placed across and on top of the circular ones. These straight elements are pre-cut long enough to protrude beyond their respective slots, and the ends are temporarily bonded on the circular shoulder of the flanges,

3) Steps 1 and 2 are repeated using the various tapes required until the full wall thickness is obtained. This alternate laying of circular and straight elements, under precisely controlled conditions, will result in a lattice of radial avenues through which the radial elements will be inserted. In principle, there should be no problem in changing from one filament to another, i. e. , from boron, as the substructure, to carbon for the heat shield.

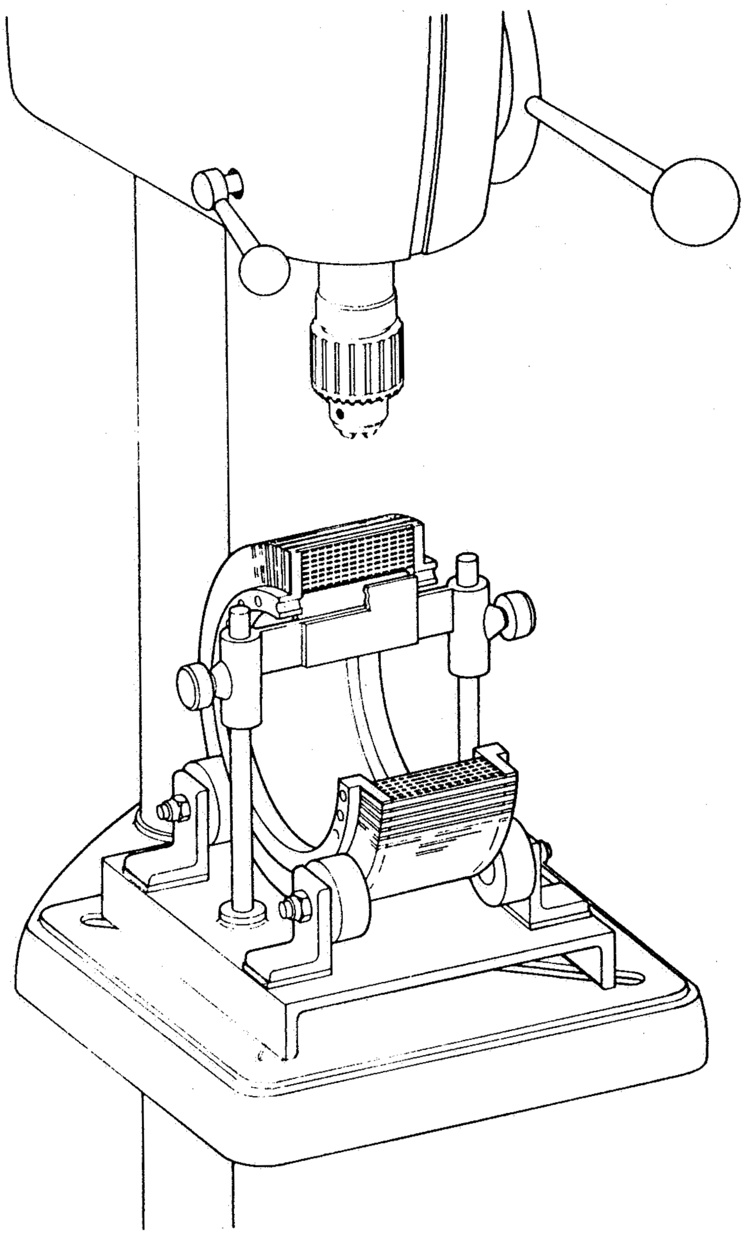

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Figure 56 PORCUPINE LOOM: SUPPORT FIXTURE FOR INSERTION OF RADIAL ELEMENTS

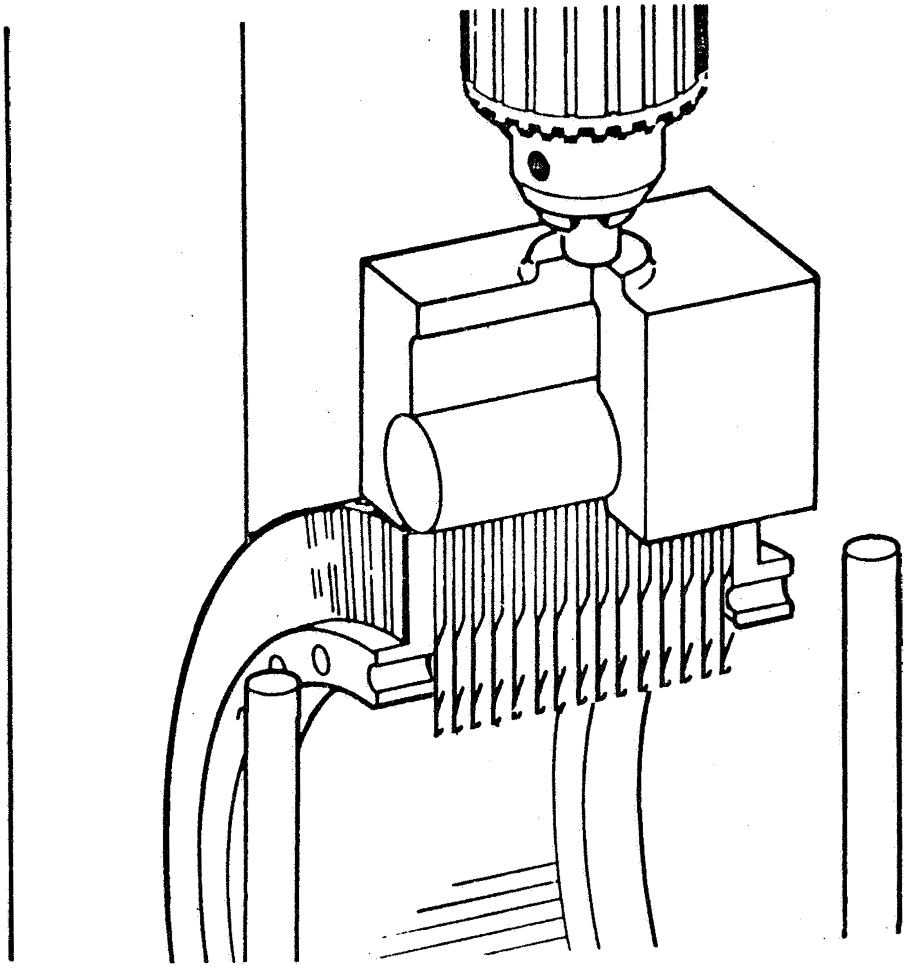

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Figure 57 PORCUPINE LOOM: RADIAL NEEDLE ASSEMBLY

4) The extra length of the straight members is trimmed flush with outer face of flange, and the mandrel placed on rollers of the radial jig. The guide pins are then removed.

5) The first wedge segment of the mandrel (which has specially designed parallel faces to facilitate this) is removed, and the anvil assembly (shown in Figure 56) is brought to bear against the underside of the wound structure. The purpose of the anvil is to prevent the hoop and axial filaments from collapsing when the needle assembly is inserted. (See next step.)

6) The latch needle assembly (Figure 57) is inserted into the line of radial holes directly above the anvil, sinking it well below the I. D. of the wound structure. If it proves necessary, the holes may first be cleared with a solid needle assembly as shown in Figure 58.

7) Yarn is then fed to the latch needles by locking a pre-threaded yarn feeder (Figure 59) onto them as shown. The yarn is disengaged from feeding frame by turning the latter 180 degrees by hand. The latches on needles are closed and the needle assembly is raised.

8) The outer ends of radial yarn are trimmed and resin bonded to outer surface. Steps 5 through 8 are repeated for all axial planes.

9) The mandrel is removed from wound structure. The latter is now ready for impregnation.

Summarizing, the hoop filaments are laid on the mandrel, using a standard winding technique. There should be no problem in accurately placing them. Regular spacing between passes of filaments (or tapes) will be left for the radial filaments; e. g., if a tape width of 0. 080 inch is used on a 0. 100-inch travel, then an 0. 020-inch gap is left for 0. 020-inch D radials, The axial filaments are laid in by hand, guided and held by the slots cut in the circular flanges at either axial end of the mandrel. (Both the hoop and axial operations are greatly facilitated by the use of prepregged tapes.) The desired radial wall thickness is ultimately attained. **A** lattice work of radial holes is thereby produced, into which knitting needles are inserted into an axial row of holes.

Figures 60 and 61 depict the present status of this winding concept producing hardware. **A** glass cylinder is shown in fabrication. Prepregged glass tape has been laid down in the hoop and axial directions. The lattice-work of radial holes can be seen. In Figure 58 the hole-alining assembly is being lowered. Glass yarn has been subsequently put in place in the radial direction. A 10-inch long 6-inch diameter cylinder

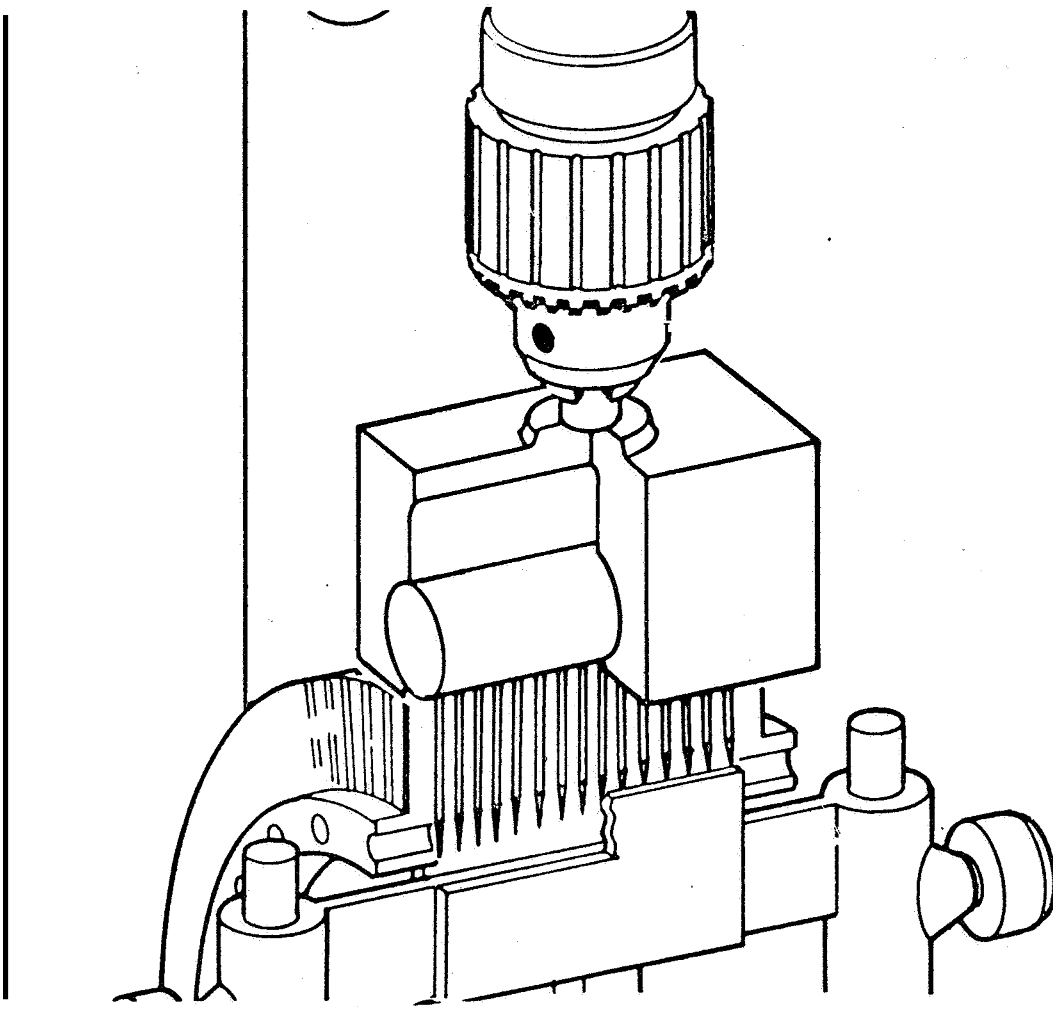

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Figure 58 PORCUPINE LOOM: AUXILIARY NEEDLE ASSEMBLY FOR CLEARING RADIAL HOLES

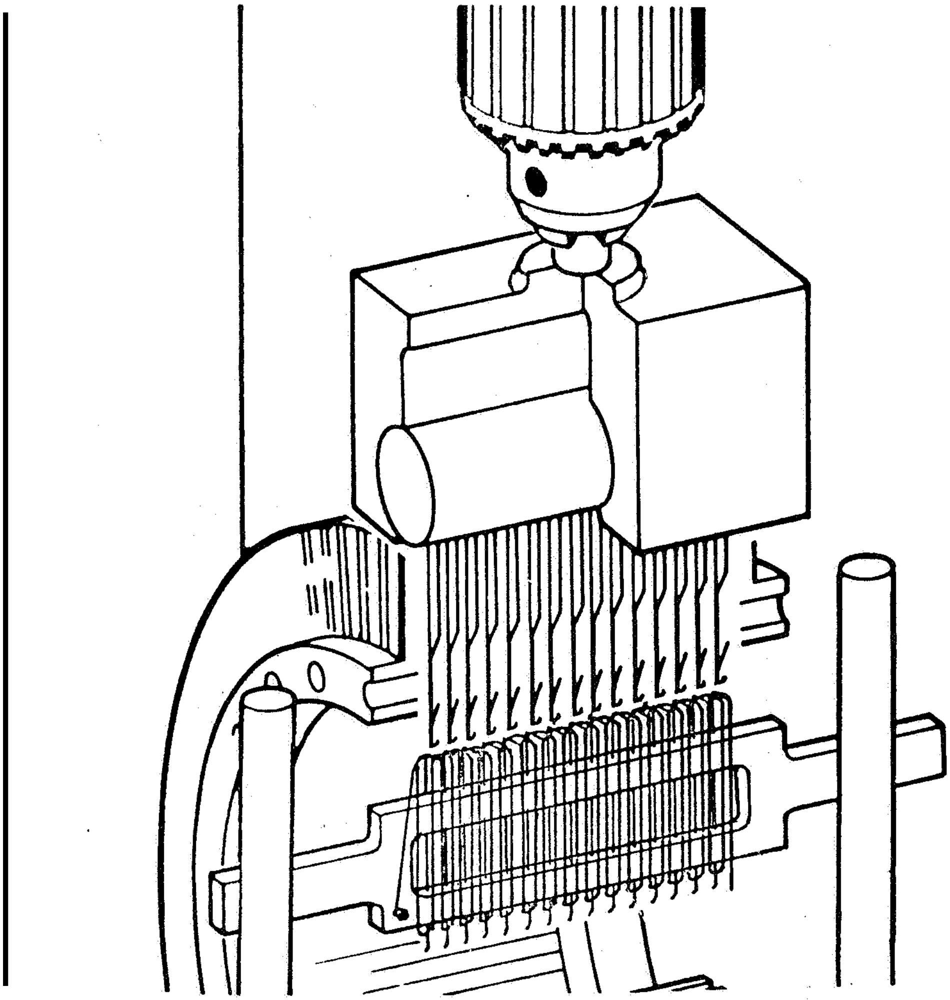

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Figure 59 PORCUPINE LOOM: RADIAL YARN FEEDER BAR

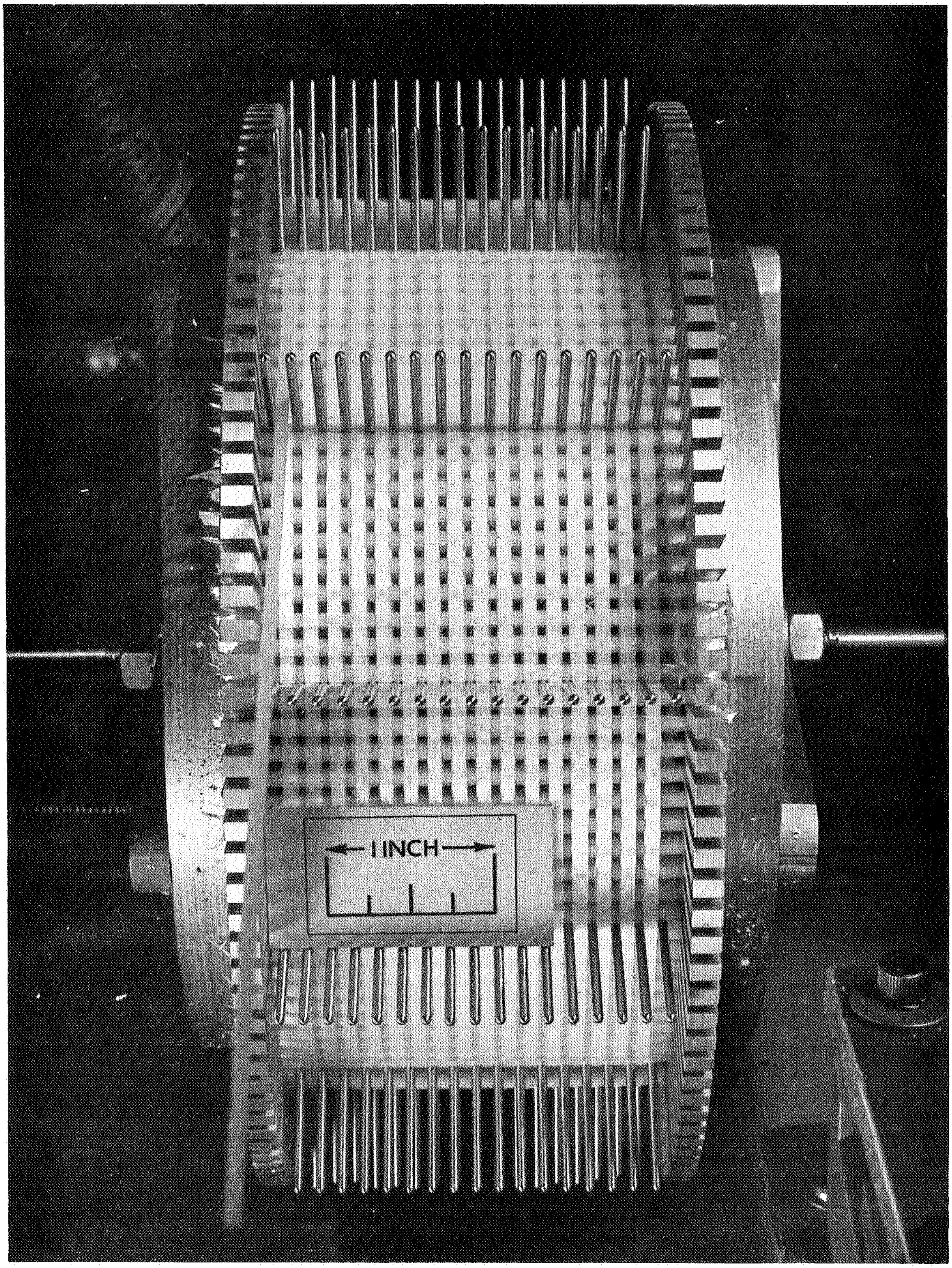

Figure 60 OVERALL VIEW PORCUPINE 3-D LOOM

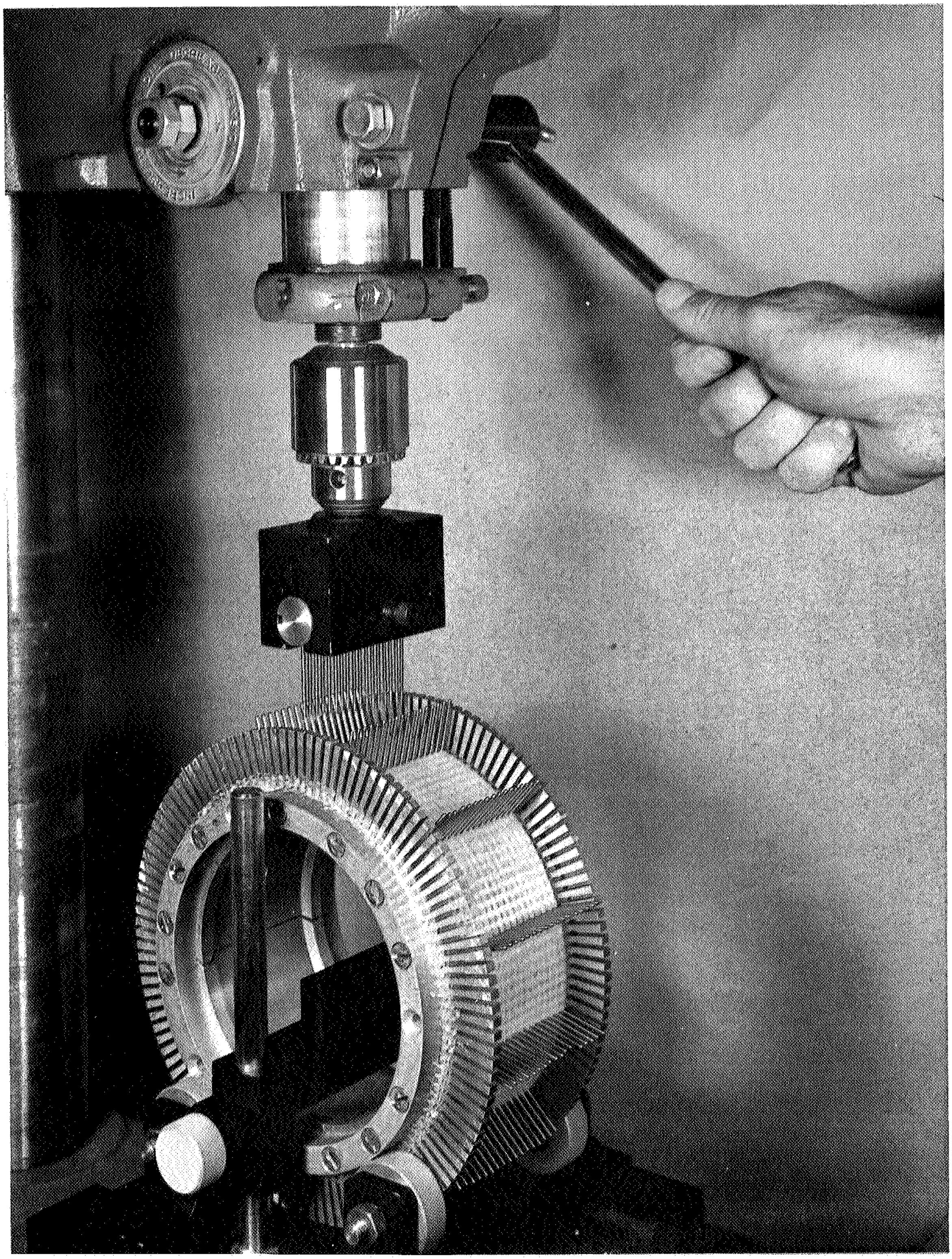

Figure 61 PORCUPINE LOOM: RADIAL YARN INSERTION

made from prepregged carbon tape is shown in Figure 62. The radials have been partially filled with prepregged pins. This is an alternative method of inserting the radial reinforcement.

10. Discussion of Results

The assessment of the potential of the nine candidate fabrication techniques, summarized in Table IV, is based on a broad investigation of existing knowledge in the textile industry. Information was obtained from the companies (large, small, specialist, and general), research institutions, and educational institutions listed in Table I. Samples of each of the methods large enough and thick enough for valid mechanical property testing were difficult to get since few companies are geared for sample preparation, especially in glass, due either to a lack of special sample equipment or to a lack of interest. The latter results from there being no industrial market for thick materials other. than asbestos, Since none of the techniques are being utilized at anywhere near the potential maximum thickness, the assessments are necessarily extrapolations from present knowledge. Thus all of the figures for maximum thickness require experimental verification. It is believed, however, that only the four methods that appear most feasible for 8-inch thick billet fabrication are worth developing that far. These are needling, double-loop fabric, multiple warp, and Avco 3-D. The mechanical test results show that these four techniques vary widely in strength. A fifth technique, braiding capable of making an 8-inch-diameter billet, ran into technical manpower problems during sample production so that no probability can be assigned to its potential. Three of the four methods, double loop, needling and Avco 3-D, can be scaled up for hardware sized billets without large scale development. In addition, considerable improvement in mechanical and ablative properties is a reasonable expectation of a thorough experimental investigation of the fabrication parameters. The other technique requires substantial development time and money to show practical fabrication methods for the fabric desired. The multiple warp concept does, however, appear to have promise in ablative properties and thus should not be dropped from consideration.

Though the other candidate techniques studied do not have the potential for very thick fabrics, the possibility exists that adequate composite strength in 8-inch-thick billets can be obtained from them. Billets could be made from a series of fabrics that might be on the order of 1/4- to 1/2-inch thickness, and the final billet would have only 10 to 20 interlaminar regions. The individual lamina would also be much stiffer. This combination of much fewer interlaminar regions and stiffer lamina may prevent cracking. If this proved correct, less expensive techniques for fabric manufacture would be available.

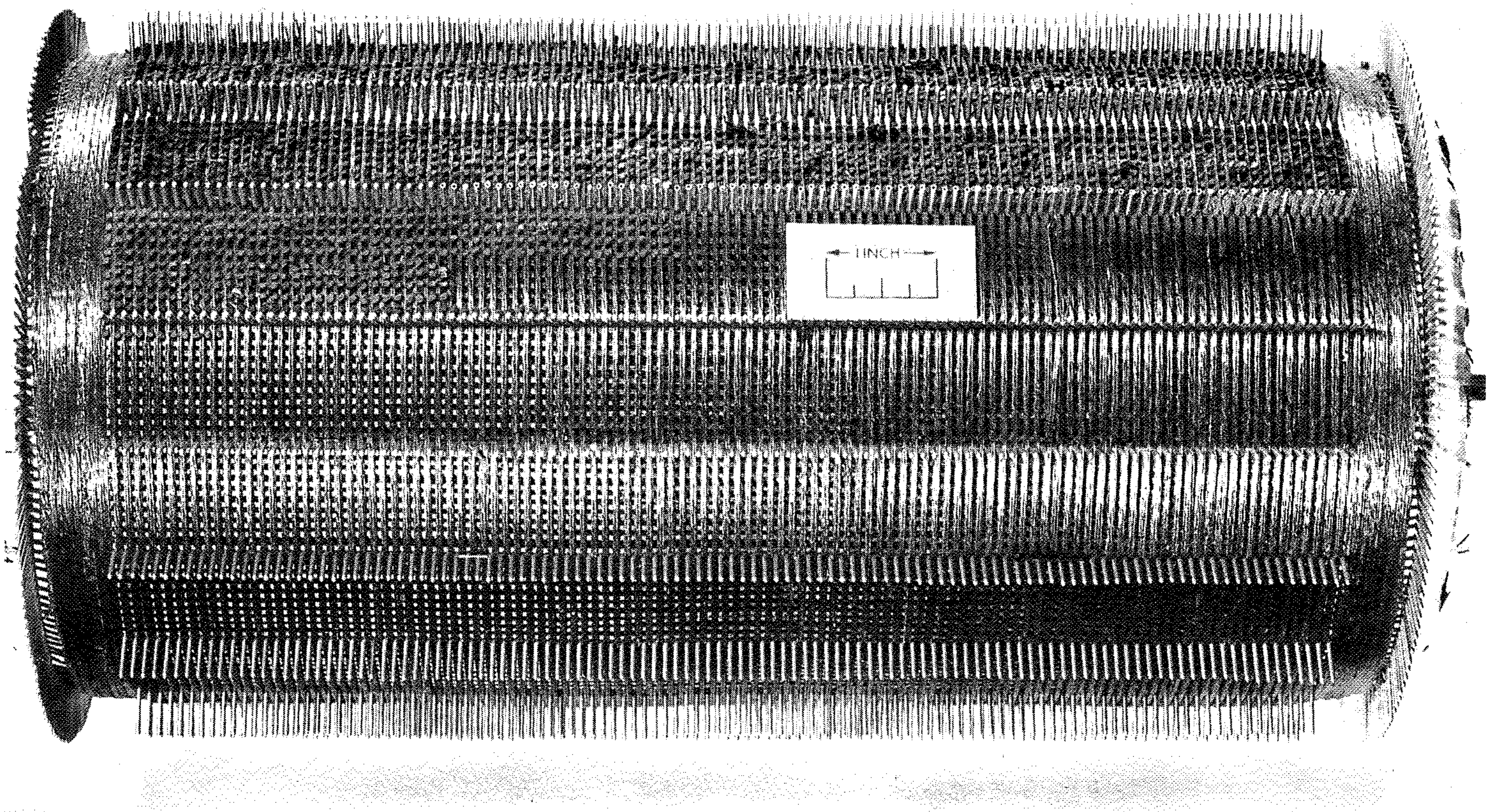

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Figure 62 PORCUPINE LOOM, 10-INCH-LONG, WITH A PORTION OF THE PRECURED RADIAL RODS INSERTED

TABLE IV

COMPARISON OF FABRICATING TECHNIQUES

Technique	Maximum Thickness Feasible (inches)	Ease of Attainment
Double Loop	Width of cloth, 24	good; method extremely flexible; fabric geometry not optimized yet
A [illegible]	12—15	good; not as flexible as above; more time consuming to manufacturing than above
Needling	unlimited	good; method very feasible
Multiple Warp	4—8	fair; method not very flexible; machine development needed
Sewing	2— [illegible]	Poor; mechanical sewing can not handle tread with such low abrasion resistance
Tufting	1/2 (normal machine); 2 (may be obtained on the Honesty machine)	Potential of Honesty machine is higher but unknown
Malimo	perhaps 3—4	fair; major machine modification needed
Braiding	unlimited	good; locking density and attainability unknown
Knitting	1/4	poor; fabric qualities poor even if made

B. RESIN IMPREGNATION AND COMPOSITE STUDIES

1. Introduction

The over-all objective of this phase of the program was to conduct a series of experimental resin impregnation studies and, as a result, develop the technology required for the impregnation of a variety of non-conventionally woven fiber reinforced structures.

The bulk of the work conducted in this portion of the over-all program was primarily concerned with developing the technology necessary for impregnating several different types of three dimensional (3-D) fiber reinforced constructions woven by Avco and outside vendors with phenolic or epoxy resin or both. In brief, the types of 3-D materials considered for evaluation included Avco 3-D, multiwarp weave, sewn fabric layers, alternating fiber matt — fabric layers needled, multilayer braiding, tufted fabric, and knitted fabric. A more specific description of the weaving processes and construction of these materials is discussed in the preceding section of this report.

Of the two classes of resin considered, the phenolics have maintained continued superiority for use in ablative applications. It must be pointed out, however, that the phenolics are much more difficult to process, due to the release of volatiles during cure, and are usually restricted to high pressure processing techniques for good consolidation. For this reason both classes of resin were pursued in the event that any significant advantages in processing or final material properties found in either resin could be exploited. The work was carried out in two phases: epoxy resin impregnation studies and phenolic resin impregnation studies. An account of the studies conducted and results of the studies with respect to the impregnation of 3-D woven materials is given in the following paragraphs.

2, Epoxy Resin Impregnation Studies

The phases of work carried out in this portion of the program concerns the preparation of a reference material, resin impregnation studies conducted on Avco and vendors 3-D materials, and the fabrication of impregnated material for mechanical property evaluation,

The initial approaches taken to impregnate the three dimensionally woven fiber structures involved the use of epoxy resin. Experimental work undertaken concerning the screening of several epoxy resins for use with Avco 3-D resulted in the selection of a flexibilized resin system based on Araldite 6005/Epon 872/$BF_3$400. The system was used throughout most of the impregnation work conducted.

a. Reference Materials

Two fiberglass-epoxy laminates (6 x 6 x 4 inches) were compression molded for evaluation of material properties. The properties generated on this material are considered representative of the behavior exhibited by quality compression molded laminates, and will serve as the reference for comparison with other materials being evaluated throughout the program.

The fabric construction used to prepare these laminates was chosen because it is more representative of the construction used in Avco 3-D, as regarding threads per square inch.

The laminates were prepared from 9-ounce fabric (18 x 18 construction, 0.011-inch thick, 150's filament-size yarn, Volan finish) and an acetone solution of the standard epoxy resin system developed for impregnating Avco 3-D Araldite 6005/Epon 872/$BF_3$400. The fabric was pre-impregnated employing a manually operated lab impregnator equipped with rubber squeeze rolls.

The resin coated fabric panels were then B-staged in a large walk-in circulating air oven for 20 to 25 minutes at 250°F, plus 10—15 minutes at 290°F.

The B-staged fabric panels were die cut (6 x 6 inches) and placed in a vented mold for processing. A molding pressure of 800 psi was applied to debulk approximately 8 inches of material. The compressed material was cured for 4 hours at 250°F and 2 hours at 275°F, postcured 6 hours at 300°F and then cooled under pressure overnight.

After curing, the laminates were trimmed, and the molded resin content and density was calculated. Results were as follows:

Code No.	Resin Content (percent)	Density (g/cm^3)
874-76	28.3	1.90
874-84	28.9	1.92

Laminate No. 874-76 has been sectioned for evaluation of physical and mechanical properties, whereas laminate No. 874-84 has been sectioned for thermal shock evaluation. Results of the mechanical and thermal shock behavior of the reference material is discussed in the test section of this report,

The physical properties of laminate No. 874-76 have been measured, and the average values of several properties of three samples were reported as follows:

Bulk Density	1870 gm/cm^3
Woven or Skeletal Density	1.320 gm/cm^3
Volume Open Porosity	0.4%*
Resin Content	29.09%

If the unit volume is set to be equal to 100 cm^3, and the fiber and resin density are known, then the following calculations can be conducted to determine the quality of the material produced.

For example, the bulk density or total weight of E-glass and resin/100 cm^3, if expressed in terms of unit volume, equals 187.0 gm.

Then:

Weight of E-glass / resin / 100 cm^3 = 187.0 gm.

Weight of E-glass / 100 cm^3 = 132.0 gm.

Weight of resin / 100 cm^3 = 55.0 gm.

From this, one can calculate the total volume occupied by each component, knowing their respective densities, and as a result obtain the total open and closed porosity:

Volume of E-glass / 100 cm^3 = 132.0 gm/2.54/g/cm^3** = 51.97 cm3

Volume of resin / 100 cm^3 = 55.0 gm/1.26/g/cm^3*** = 43.65 cm^3

Total Volume of E-glass / resin / 100 cm^3 = 95.62 cm^3

Total open and closed porosity = 100.00 cm^3 - 95.62 cm^3
= 4.38 cm^3 or 4.38%

In addition, a theoretical density can be calculated if it is assumed that the porous volume could have been occupied by resin to obtain maximum density.

Weight of E-glass/100 cm^3 = (51.97 cm3) (2.54 g/cm3) = 132.0 gm

Theoretical Weight of resin/100 cm^3 = (43.65 cm3 + 4.30 cm3)
(1.26 g/cm^3) = 60.5 gm

Total weight of E-glass t new weight of resin/100cm^3 = 192.5 gm.

*Measured by air pycnometer

**T.J. Humphrey, "New Glass Fibers," presented at the 21st Conference of the Society of Plastics Industry, Inc. February 1966, Chicago, Illinois.

'#*Measured on pure resin

Then:

Theoretical Density = 192.5 gm/100 cm3 or 1.925 gm/cm3

From this a densification efficiency can be calculated by the following expression:

$$\text{Densification efficiency} = \frac{\text{Bulk density}}{\text{Theoretical density}} \times 100$$

$$= \frac{1.870\ g/cm^3}{1.925\ g/cm^3} \times 100$$

$$= 97.14\%\ \text{dense.}$$

Another useful term may be defined as

$$\text{Impregnation Efficiency} = \frac{\text{Actual weight of resin/ 100 cm}^3}{\text{Theoretical weight of resin/ 100 cm}} 3 \times 100$$

$$= \frac{55.0\ gm}{60.5\ gm} \times 100$$

$$= 90.91\%\ \text{impregnated}$$

These calculations have been made for each of the samples evaluated in this program, and will be discussed in more detail at the end of this secion of the report.

b. AVCO 3-D

Several approaches were evaluated to define and overcome the problems associated with the impregnation of densely woven fiber constructions. During the initial stages of this work, involving the use of various low viscosity epoxy resin systems, it was found that complete impregnation could be achieved by simple vacuum impregnation; but, due to the combined effect of stresses induced by shrinkage of the resin during cure and differential expansion between the resin matrix and the rigidly woven Avco 3-D structure, the resin matrix fractured severely. As a result of this problem,various flexibilized resin systems were tried that would be less strain sensitive and have lower shrinkage characteristics. This, however, was accomplished at the expense of increasing the resin viscosity, and it was found that external pressure was required in addition to vacuum to achieve a complete impregnation,

For this reason, the apparatus shown in Figure *63* was constructed. The vacuum source was attached to the lower end of the apparatus, and

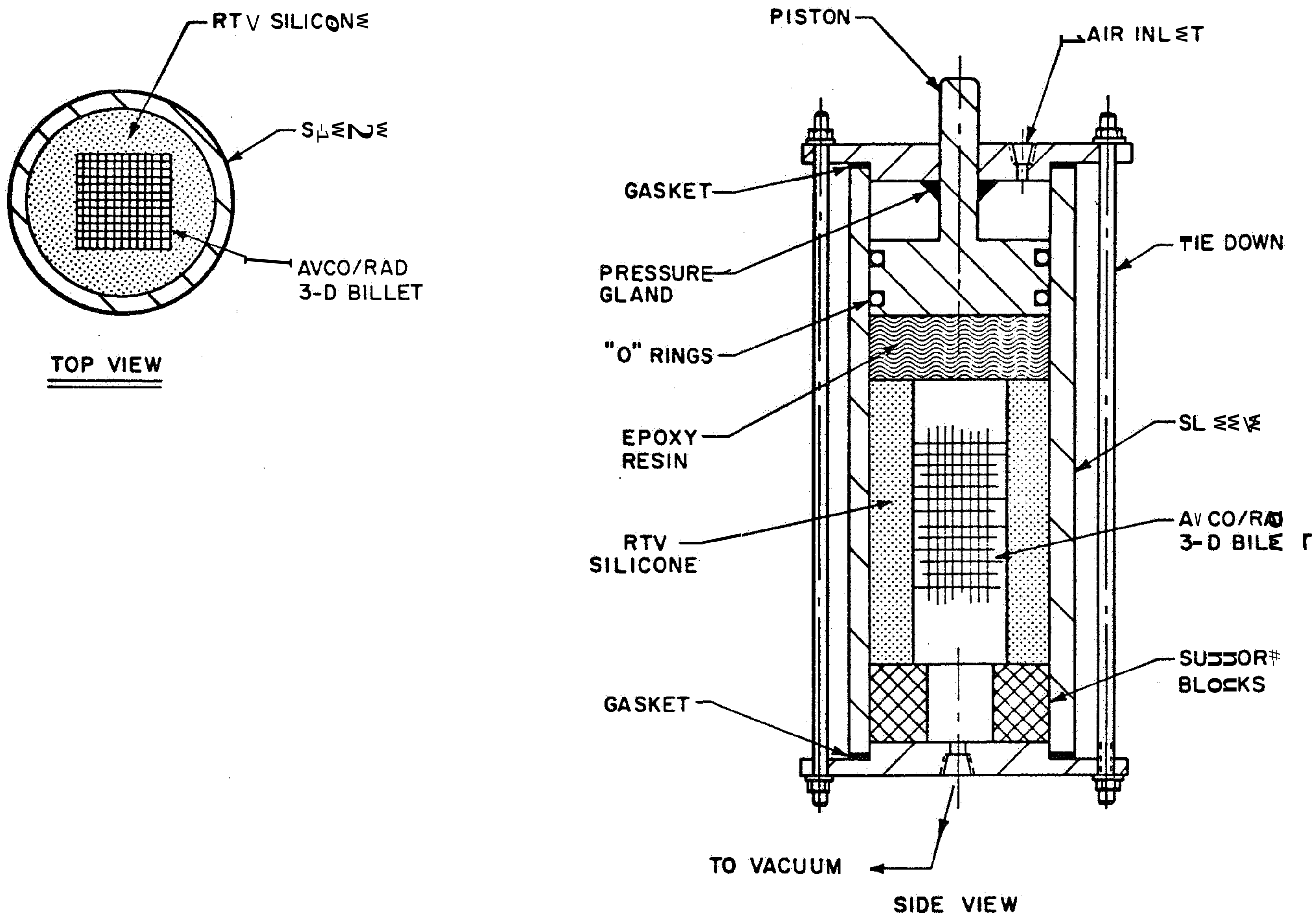

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Figure 63 SCHEMATIC OF VACUUM PRESSURE IMPREGNATION SYSTEM regulated house air pressure was used to move the piston. This apparatus was used to impregnate the 3- x 3- x 4 1/2-inch billets of Avco 3-D material.

The flexibilized resin system selected for impregnating Avco 3-D is formulated, cured, and postcured as follows:

Ciba—Araldite 6005:	50. 0 pt by wgt
Shell—Epon 872:	50. 0 pt by wgt
BF_3 400:	3. 0 pt by wgt

Cure: 16 hr at 235°F

Postcure: 5 hr at 300°F

The physical characteristics of the uncured resin system were measured and recorded as follows:

Specific Gravity: 1. 085 at 200°F

Viscosity, CPS: 950—1000 at 200°F

The vacuum-piston pressure impregnating procedure used is described in detail in the appendix of this report.

Several billets of Avco 3-D (3 x 3 x 4 1/2 inches) and one block of Raypan-sewn multiwarp fabric layers (5 x 3 x 3 inches) have been impregnated in this manner, The materials were sectioned for physical and mechanical property evaluation. Results of the mechanical properties of these materials are reported in the test section of this report. The physical properties of Avco 3-D, however, are reported in Table V.

c, Vendor 3-D Materials

Various types of 3-D construction obtained from vendors, which are described in detail in the weaving section of this report, have been impregnated with the standard epoxy resin system for mechanical property evaluation for comparison with the reference and Avco 3-D material.

In general, the source and type of constructions obtained from the various suppliers are listed on the following page:

Avco Code No.	No. 909-107-50	No. 909-41-52
Reinforcement	S-glass	S-glass
Bulk Density (g/cm^3)	1. 79	1. 83
Woven Density (g/cm^3)	1. 24	1. 31
Total Open and Closed Porosity (percent)	6. 6	6. 2
Total Open Porosity (percent:::)	0. 9	0. 8
Resin Content (percent)	30. 3	28. 3
Theoretical Density (gm/cm^3)	1. 87	1.90
Densification Efficiency (percent)	95. 6	94. 6
Impregnation Efficiency (percent)	86. 9	86. 9

Supplier	Name of Samples	Basic Construction
J. P. Stevens	Trials Nos 1 to 6	NeedledMatt-Fabric
J. P, Stevens	Trials Nos 1 to14	Multiple Tufted Fabric Layers
J. P. Stevens	2 types	Multiwarp Fabric
Through H. Simmons (consultant) woven by H. Harwood & Son	2 types 1 type	Needled Matt-Fabric Sewn Fabric Layers
Valrayco	2 types	Multilayer Braid, No Lock

The series of reinforcements--Trials Nos 1 to 6--supplied by J. P. Stevens are typical examples of several variations in needling parameters that are described in detail in Table 111. The tufted fabrics labeled

*As measured in air pycnometer

1, 2, 4, 6, 8, 10, and 14 refer to the number of plies of base fabric through which the tufting was done to determine the maximum thickness obtainable by this method. Only the 10- and 14-ply materials were examined in this investigation, except for problem definition studies.

All of the materials were woven from continuous S-glass, with the exception of one material supplied by H. Simmons, which was prepared from Beta-glass (staple fiber).

The early stages of this work consisted of definition of the problem areas encountered in impregnating these various samples. The experimental work was conducted on 1-layer tufted fabric, needled matt-fabric, and multilayer braid reinforcement, both utilizing solvent-based and 100-percent solids epoxy resin for impregnation. The development of a single process technique suitable for all reinforcements was desired. The use of both vacuum impregnation and an external pressure source would be required for impregnating with the standard epoxy resin.

The results of these experimental impregnation showed that--

1) The reinforcement had to be firmly tied down (Figure 64) to restrict the movement of the sample during impregnation and to reduce the distortion due to non-uniform shrinkage during curing.

2) A heavy pure resin layer on the top surface of the sample during cure caused distortion of the sample and had to be kept to a minimum.

3) The solvent-based epoxy resin system vacuum impregnated quite rapidly without the use of additional external pressure, but the time required for efficient removal of the volatile solvent was considerable.

4) The 100-percent solids epoxy resin system gave complete impregnation, if, in addition to vacuum impregnation, was added pressure cycles of 5—90 psi in 15 minute intervals. During the course of this work, however, it was found that the time interval during cycling was critical in getting complete impregnation, and, as a result 15 minute time intervals were established as minimum.

5) The use of vacuum impregnation plus pressure applied from a hydraulic press (Figure 65) could be utilized to consolidate the material to a predetermined density by the use of mold stops.

6) One drop of SAG antifoam agent was essential to de-aerate the 100-percent solids resin.

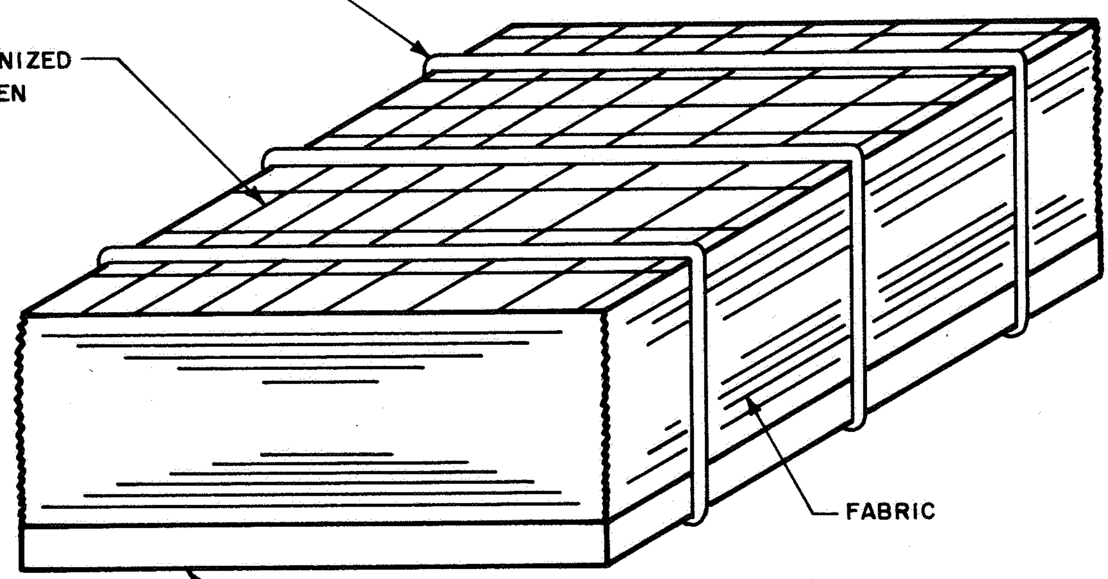

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Figure 64 FABRIC SUPPORT ASSEMBLY

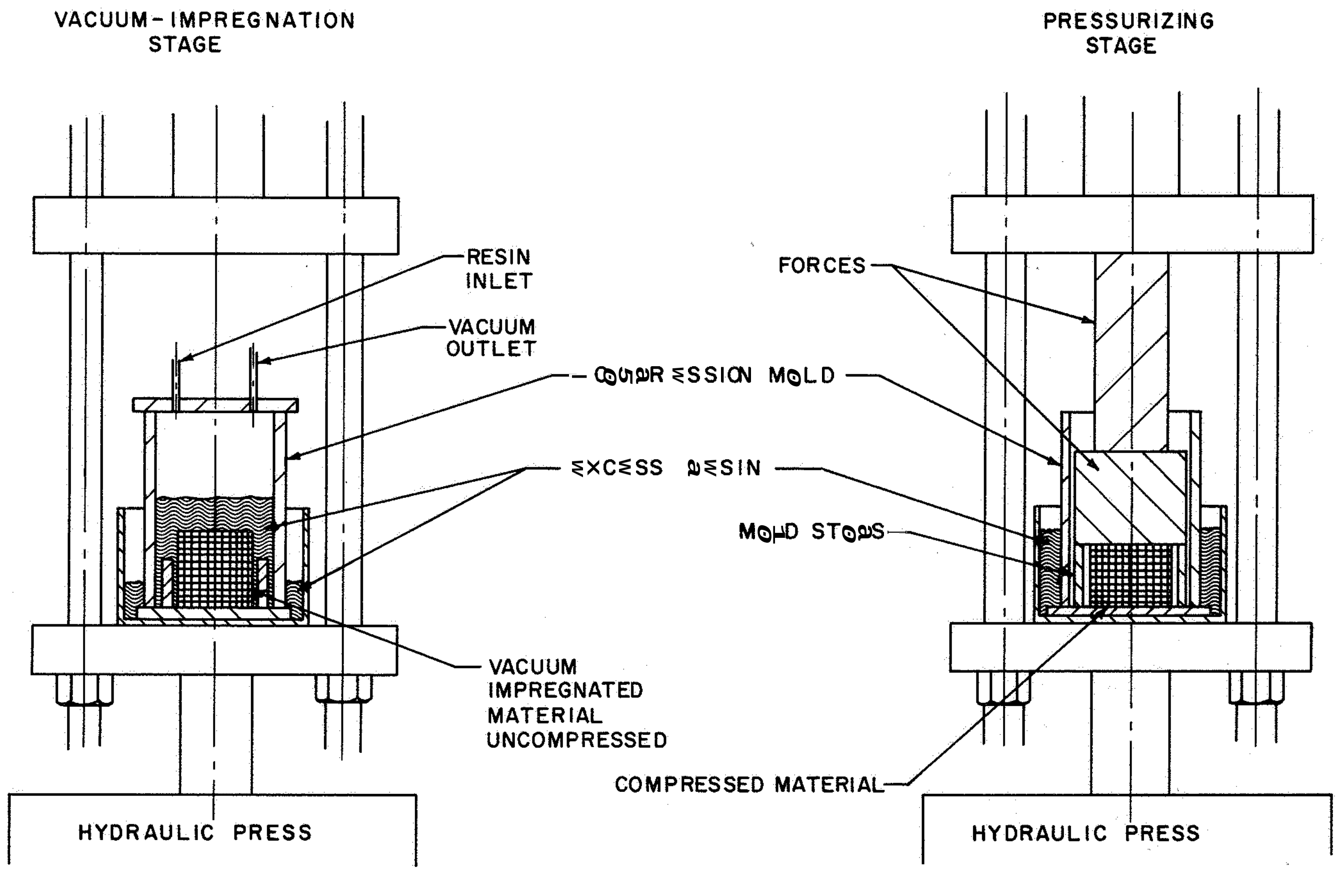

Figure 65 SCHEMATIC OF VACUUM-PRESSURE PRESS MOLDING TECHNIQUES

As a result of these findings, two resin impregnation techniques were selected for processing the candidate fabrics. The methods are briefly described as (1) vacuum impregnation—air pressure cycling and (2) vacuum impregnation—press molding. The former method was used to impregnate most of the reinforcements supplied in an as-received form, whereas the latter method was used to adjust the resin content to the level obtained in the reference laminates, i.e., 25—30-percent resin for a more valid comparison of the materials.

The detailed procedures employed in each of the methods is given in the appendix of this report.

Most of the materials supplied by the vendors have been impregnated for mechanical property evaluation. A listing of the materials impregnated during this phase of work is compiled below.

Construction	Supplier	No. of Samples	Size (inch)	Process Method
Needled Matt Fabric	H. Simmons	3	6x6x3/4	Vacuum—air pressure
Needled Matt Betaglass	H. Simmons	1	6x6x3/8	Vacuum—air pressure
Needled Matt Trial No. 1	J. P. Stevens	2	9x4x3/4	Vacuum—air pressure
Needled Matt Trial No. 2	J. P. Stevens	2	9x5x1/4	Vacuum—press molded
Needled Matt Trial No. 3	J. P. Stevens	2	9x6x3/4	Vacuum—air pressure
Needled Matt Trial No. 6	J. P. Stevens	2	9x6x3/4	Vacuum—air pressure
Needled Matt Trial No. 6	J. P. Stevens	2	9x5x3/8	Vacuum—press molded
Tufted Fabric Layers, 1 ply	J. P. Stevens	1	9x6x1/16	Vacuum—air pressure
Tufted Fabric Layers, 1 ply	J. P. Stevens	1	9x6x1/16	Vacuum—air pressure
Tufted Fabric Layers, 1 ply	J. P. Stevens	1	9x6x1/16	Vacuum—air pressure
Tufted Fabric Layers, 10 ply	J. P. Stevens	2	9x6x1/4	Vacuum—air pressure
Tufted Fabric Layers, 14 ply	J. P. Stevens	2	9x6x1/4	Vacuum—air pressure
Multiwarp Weave	J. P. Stevens	2	9x21/2 x1/4	Vacuum—air pressure
Multiwarp Weave	J. P. Stevens	1	9x1x1/4	Vacuum—air pressure
Sewn Fabric Layers	H. Simmons	1	5x21/2x3/4	Vacuum—air pressure
Multilayer Braid, no lock	Valrayco Co.	2	3 dia by 6 long	Vacuum—air pressure

Physical properties such as bulk density, porosity, resin content, etc., have been measured on these materials and are presented in Tables VI to VIII. The data have been treated in the manner described previously to show the effectiveness of the impregnation.

d. New Resin Impregnation Studies

Results of the analytical method used to determine the degree of impregnation strongly indicated the need for more efficient resin impregnation. Whether improvements could be made to upgrade the quality of the materials through processing or by selection of a new resin system required investigation.

On this basis, a low viscosity cyclo-aliphatic based resin system was formulated for comparison with the standard epoxy resin system used throughout the program as an impregnate. The viscosity of the new resin system, Unox 221/Methyl "Nadic" Anhydride/Ethylene Glycol, was recorded as being 40 cps at 150°F.

The approaches taken to evaluate the new resin and to determine the effects of high pressurizing on impregnation with the standard epoxy were as follows.

1) Approach No. 1. -- Samples of E-glass fabric were precompacted (Figure 66) to a density of 1.25 g/cm^3 for use with the standard and new epoxy resins. The precompacted samples were processed through the use of vacuum impregnation and 5—90 psi air pressure cycles applied in 15-minute intervals.

Results of this work are presented in Table IX. It can be readily seen from the values reported that the new resin system evaluated (No. 909-15) provides a much more efficient impregnation when compared to laminate No. 909-13. To demonstrate if the same degree of impregnation would be achieved with the standard epoxy resin by the use of higher pressure cycling, and to determine the effect of compacted density, the following approach was taken.

2) Approach No. 2. -- Two precompacted samples of E-glass fabric were prepared. The approximate compacted densities of each were 1.23 g/cm^3 and 1.32 g/cm^3. Both samples were processed by the use of vacuum impregnation and 5—350 psi argon pressure cycles applied in 5-minute intervals.

The quality of these materials was assessed by determining the physical characteristics and by photographing a cross-section taken from the center of the samples to indicate the extent of voids noticed in each laminate after processing (See Figure 67.)

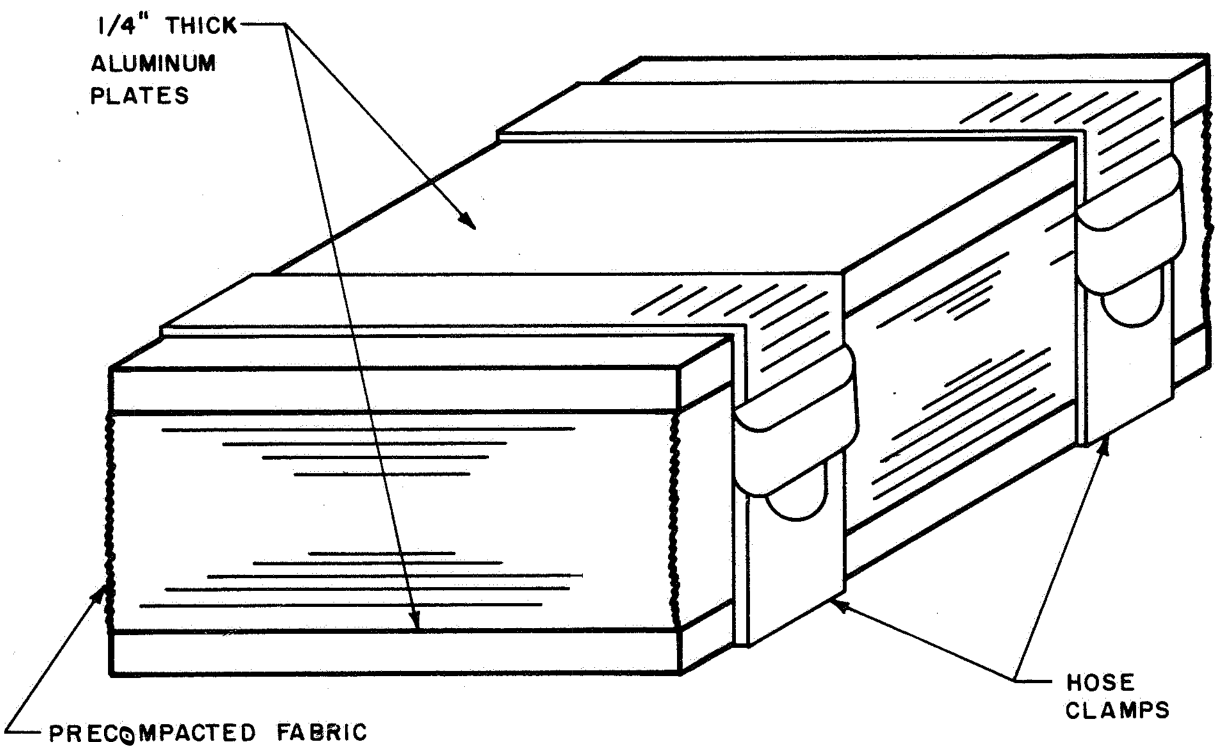

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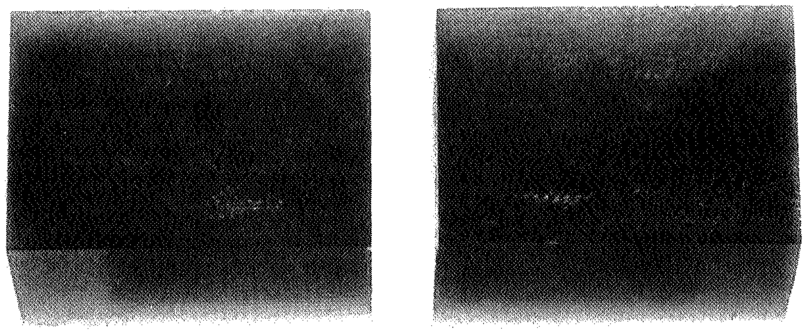
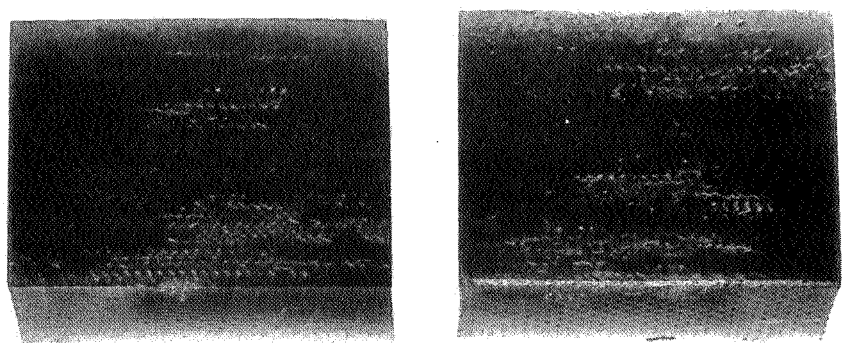
Figure 66 COMPACTED FABRIC ASSEMBLY



LAMINATE NO. 910-45

COMPACTED DENSITY - 1.25 g/cc



LAMINATE NO. 910-47

COMPACTED DENSITY - 1.35 g/cc

16080

Figure 67 CROSS-SECTION PHOTOGRAPHS OF SAMPLES FROM NEW RESIN IMPREGNATION STUDIES NO. 16080

TABLE VI

RESULTS OF EPOXY-IMPREGNATED NEEDLED MATT-FABRIC SAMPLES

Avco Code No.	909-59	909-68	909-83	909-85	909-101	909-103	909-114
Vendor	J. P. Stevens	J. P. Stevens	I. P. Stevens	J. P. Stevens	I. P. Stevens	J. P. Stevens	J. P. Stevens
Vendor Code	Trial No. 1	Trial No. 1	Trial No. 2	Trial No. 2	Trial No. 3	Trial No. 3	Beta-glass
Method of Impregnation*	AP	AP	PM	PM	AP	AP	AP
Bulk Density (g/cm^3)	1.31	1.37	1.99	1.97	1.79	1.75	1.41
Woven Density (g/cm^3)	0.42	0.41	1.57	1.51	1.18	1.16	0.31
Total Open and Closed Porosity (percent)	7.7	7.4	3.9	4.6	4.5	6.4	0.2
Total Open Porosity (percent)**	0.7	0.8	4.9	2.5	3.7	1.3	0.0
Resin Content [percent)	69.3	70.2	20.8	20.9	34.0	34.0	77.9
Theoretical Density (g/cm^3)	1.47	1.46	2.03	2.03	1.84	1.83	1.42
Densification Efficiency (percent)	93.1	93.6	97.5	97.1	97.0	95.6	99.4
Impregnation Efficiency (percent)	90.7	91.2	89.2	87.7	91.6	88.1	99.2
Avco Code No.	**909-145**	**909-146**	**909-147**	**909-148**	**909-56-1A**	**909-56-2A**	**909-81**
Vendor	J. P. Stevens	J. P. Stevens	J. P. Stevens	J. P. Stevens	H. Simmons	H. Simmons	H. Simmons
Vendor Code	Trial No. 6	Tnal No. 6	Trial No. 6	Trial No. 6	----		----
Method of Impregnation*	AP	AP	PM	PM	AP	AP	AP
Bulk Density (g/cm^3)	1.51	1.57	1.89	1.80	1.46	1.46	1.48
Woven Density (g/cm^3)	0.68	0.77	1.33	1.21	0.57	0.57'	0.62
Total Open and Closed Porosity (percent)	7.7	5.8	1.8	4.2	6.9	7.0	7.1
Total Open Porosity (percent)*:	1.3	0.0	0.1	0.1	0.0	0.3	3.3
Resin Content (percent)	54.6	51.1	29.8	32.9	60.7	60.6	58.1
Theoretical Density (g/cm^3)	1.60	1.64	1.92	1.86	1.54	1.54	1.57
Densification Efficienty (percent)	94.2	95.5	98.8	97.2	94.4	94.3	94.3
Impregnation Efficiency (percent)	89.9	91.6	96.1	91.8	91.0	90.9	90.6

*AP = Air Pressurized: PM = Press Molded
**As measured in air Pycnometer

TABLE VII

RESULTS OF EPOXY IMPREGNATED MULTIWARP FABRIC, SEWN FABRIC AND MULTILAYER BRAID SAMPLES

	Multiwarp Fabric		Sewn Fabric	Multilayer Braid	
Avco Code No.	910-10B	910-10C	910-9	909-105	909-106
Vendor	J. P. Stevens	J. P. Stevens	H. Simmons	Valrayco	Valrayco
Method of Impregnation*	AP	AP	AP	AP	AP
Bulk Density (g/cm^3)	1.67	1.62	1.82	1.85	1.87
Woven Density (g/cm^3)	1.00	0.90	1.25	1.32	1.36
Total Open and Closed Porosity (percent)	6.4	6 6	5.0	4.9	4.9
Total Open Porosity (percent)**	3.4	5.0	2.6	2.3	2.3
Resin Content (percent)	40.4	44.4	31.0	28.7	27.3
Theoretical Density (g/cm^3)	1.75	1 71	1.88	1.91	1.93
Densification Efficiency (percent)	95.4	95 2	96.6	96.8	96.8
Impregnation Efficiency (percent)	89.3	89 8	89.9	89.5	89.2

*AP = Air Pressurized
**As measured in air pycnometer

TABLE VIII

RESULTS OF EPOXY-IMPREGNATED TUFTED FABRIC SAMPLES

Avco Code No.	909-62	909-75	910-8
Vendor	J. P. Stevens	J. P. Stevens	J. P. Stevens
Vendor Code	14 ply	10 ply	10 ply back to back
Method of Impregnation*	AP	AP	AP
Bulk Density (g/cm^3)	1.67	1.66	1.54
Woven Density (g/cm^3)	0.93	0.97	0.80
Total Open & Closed Porosity (percent)	4.0	6.2	7.9
Total Open Porosity (percent)**	0.0	3.6	3.8
Resin Content (percent)	44.1	41.5	49.0
Theoretical Density (g/cm^3)	1.72	1.74	1.65
Densification Efficiency (percent)	97.0	95.5	93.3
Impregnation Efficiency (percent)	93.5	89.8	95.0

* AP = Air Pressurized

** As measured in air pycnometer

TABLE IX

RESULTS OF N[illegible] RESIN IMPREGNATION STUDIES

Avco Code No.	909-13	909-15	909-45	909-47
Reinforcement	E-glass	E-glass	E-glass	E-glass
Resin System	Araldite 6005/ Epon 872/$BF_3$400	Unox 221/MNA ET. Glycol	Araldite 6005/ Epon 872/$BF_3$400	Araldite 6005/ Epon 872/$BF_3$400
Bulk Density (g/cm^3)	1. 84	1. 87	1. 82	1. 87
Fabric Density Compacted (g/cm^3)	1 26	1 26	1 23	1 32
Total Open and Closed Porosity (percent)	4. 7	0. 1	5. 1	4. 6
Total Open Porosity (percent)*	0. 5	0. 7	0. 3	[illegible]
Resin Content (percent)	31. 2	33. 1	32. 1	[illegible]
Theoretical Density (g/cm^3) (percent)	1 90	1 8[illegible]	1 8[illegible]	1 93
Densification Efficiency (percent)	96. 9	9[illegible]	96. 6	97. 0
Impregnation Efficiency (percent)	9[illegible]. 7	99. 4	90. 1	90. 4

*As measured in air pycnometer.

The physical characteristics of laminates No. 909-45 and No. 909-47 were determined on 3/4-inch dia x 3/4-inch-high corings taken from areas surrounding the voids, and results are given in Table VIII for comparison with results obtained on laminates No. 909-13 and No. 909-15.

As a result of this new work, the following conclusions can be made:

a) Low-viscosity and low-shrinkage resin characteristics are essential in achieving high quality laminates,

b) Utilization of higher pressure (350 psi) to provide more efficient impregnation requires further study to assess its value in improving the quality of materials produced, The voids contained in laminates **Nos** 909-45 and 909-47 were probably caused by (1) insufficient removal **of** air during shorter vacuum impregnation cycle, (2) insufficient flow time during shorter pressure cycle to reach control portion, or (3) partial solubility of the pressurizing medium (Argon at 350 psi) in the resin while under pressure, with no way to diffuse out after gellation and cure. The difference in the void content between the laminates, however, has been attributed to the difference in precompaction densities,

3. <u>Phenolic Resin Impregnation Studies</u>

a. Phenolic Impregnation

Several approaches have been evaluated in attempts to develop a near void-free phenolic resin matrix for Avco 3-D reinforced structures.

At the onset of this phase of work, the criteria set for an approved method were based upon achieving a final density of 1.90 gm/cm^3 and a total volume porosity of less than 10 percent through the use of E-glass fabric and 28- to 32-percent phenolic resin. Although these values were somewhat arbitrarily chosen, it was felt that the final properties desired were equivalent to values obtained on acceptable compression molded laminates.

To expedite program efforts-- and because of the high costs **of** the 3-D structures for experimental study--E-glass fabric (Volan A-181 construction) was chosen for the initial impregnation studies. Fabric samples were prepared by compressing approximately 200 layers of dry cloth between two metal plates that were fastened with hose clamps. (See Figure 66.) The fabric was compacted to a predetermined density (1.35 to 1.40 g/cm^3) to simulate the woven density of the 3-D structures

TABLE X

RESULTS OF PHENOLIC IMPREGNATION STUDIES

Code No.	Type Reinforcement	Type Resin	Woven or Compacted Density (g/cm^3)	Process Conditions	Density (g/cm^3)	Porosity (percent)	Resin Content (percent)
874-[illegible] (40)	Avco 3-D	SC100[illegible]	1 45	Soaked at 130°F. Gelled at 180°F. Press cured 1.4. Gelled resin to 350°F	1.79	16 0	19 0
874-56	181 Fabric	SC1008	1.51	Soaked and gelled at 150°F. Press cured to 350°F	1 80	16 0	16.1
874-36	181 Fabric	SC1008	1.50	Soaked and gelled at 150°F. Press cured in gelled resin to 350°F	1 [illegible]	18 4	17.6
[illegible] (28)	Avco 3-D	SC1008	1.44	Soaked and gelled at 150°F. Vacuum bag cured to 350°F	1 76	13 3	18.2
874-[illegible]	181 Fabric	SC1008	1.39	Soaked and gelled at 180°F. Cured in gelled resin to 350°F	1 67	[illegible] 8	16.8
874-3[illegible]	181 Fabric	SC1008	1.41	Soaked at 180°F. Dried at 200°F. Cured to 350°F	1.70	----	17.2
87 [illegible]	181 Fabric	[illegible]1008	1.37	Soaked and gelled at 180°-2[illegible]0°F. Cured to 350°F	1.67	[illegible]1 3	18.0
8 74-4 (32)	Avco 3-D	SC1 [illegible]8	1.41	Soaked and gelled at 150°-180°F. Cured to 350°F	1.69	[illegible]3.5	16.6
8 74-[illegible]	181 Fabric	Co[illegible]b No. 39[illegible]	1.43	Soaked and gelled at 150°-180°F. Cured to 350°F	1.82	----	21.4
8 74-6 (41)	Avco 3-D	SC1 0[illegible]	1.43	Soaked at 150°F. Dried at 180°F (3 times). Cured to 350°F	1.77	14.6	19.5

TABLE XI

COMPARISON OF RESULTS OF PHENOLIC IMPREGNATION AND EPOXY RE-IMPREGNATION STUDIES

Code No.	Resin	Bulk Density (g/cm^3)	Woven Density (g/cm^3)	Total Porosity (percent)	Open Porosity (percent)	Resin Content (percent)	Theoretical Density (g/cm^3)	Densification Efficiency (percent)	Impregnation Efficiency (percent)
874-36	Phenolic	1.82	1.50	15.7	18.7	17.6	2.02	90.1	61.5
	Phen.-Epoxy	2.01	1.50	0.8	0.9	25.4	2.02	9[illegible].5	98.1
874-38	Phenolic	1.70	1.41	21.6	----	17.2	1.98	87.8	5[illegible].6
	Phen.-Epoxy	1.9[illegible]	1.41	1.8	0.8	27.0	1.98	98.9	9[illegible].5
874-40	Phenolic	1.[illegible]7	1.39	23.2	14.7	16.8	1.97	85.0	48.7
	Phen.-Epoxy	1.[illegible]4	1.39	2.5	1.1	28.4	1.97	98.[illegible]	94.7
874-54	Phenolic	1.[illegible]7	1.37	22.4	21.3	18.0	1.95	85.5	5[illegible].2
	Phen.-Epoxy	1.[illegible]1	1.37	3.4	1.7	28.3	1.95	97.8	9[illegible].5
874-56	Phenolic	1.80	1.51	17.7	16.0	16.1	2.03	89.0	56.[illegible]
	Phen.-Epoxy	1.81	1.51	16.9	16.2	16.7	2.03	89.4	58.[illegible]
874-82	Phenolic	1.82	1.43	12.9	----	21.4	1.99	92.0	70.3
	Phen.-Epoxy	1.95	1.43	2.7	1.8	26.7	1.99	98.[illegible]	9[illegible].7
874-48 (28)	Phenolic	1.76	1.44	17.0	13.3	18.2	1.99	88.5	5[illegible].4
874-74 (32)	Phenolic	1.[illegible]9	1.[illegible]	21.9	13.7	16.6	1.97	86.0	53.0
	Phen.-Epoxy	1.[illegible]2	1.[illegible]	3.7	1.0	26.8	1.97	97.[illegible]	91.6
874-72 (40)	Phenolic	1.7[illegible]	1.45	15.0	16.0	19.0	1.98	9[illegible].4	[illegible]4.2
	Phen.-Epoxy	1.9[illegible]	1.45	1.8	1.0	26.0	1.98	9[illegible].0	[illegible]6.2
874-86 (41)	Phenolic	1.77	1.43	15.9	14.6	19.5	1.97	90.0	62.9
	Phen.-Epoxy	1.91	1.43	4.8	2.1	25.2	1.97	97.0	88.8

*As measured in air pycnometer

being produced and the reference material. Monsanto SC 1008 was used almost exclusively in this study for the phenolic resin system. Although other classes, such as castable and powdered phenolics, were seriously considered, they were' found to be impractical for this application.

In the course of the impregnation studies, it was found that a resin specific gravity of 1.050 and a viscosity of 25–50 cps (Brookfield) were required for complete impregnation with the phenolic varnish. These conditions were achieved by simply heating the "as-received" resin (sp. gr. , 1.075) to 150—-180°F.

As the resin aged in cold storage (30°F), however, it became necessary to dilute the resin with additional solvent (isopropanol) to achieve the desired resin characteristics for impregnation,

Compacted fabric samples were placed in 150—180°F phenolic resin, As the resin was heated, solvent volatiles slowly evolved without foaming of the resin, When the resin reached a gelled condition, the residual volatile content was measured and, in most cases, was found to range between 15 and 20 percent. At this stage, the impregnated parts were removed from the gelled resin bath for further processing.

The first group of samples was processed by soaking in 150—-180°F resin for various time periods, then cured to 350°F with the aid of external pressure; whereas the second group was gelled and processed without application of external pressure, In addition, one of the samples (,No. 874-82) was treated with new high solids (75 percent) resin-Colab 397. Results of these experiments appear in Table X.

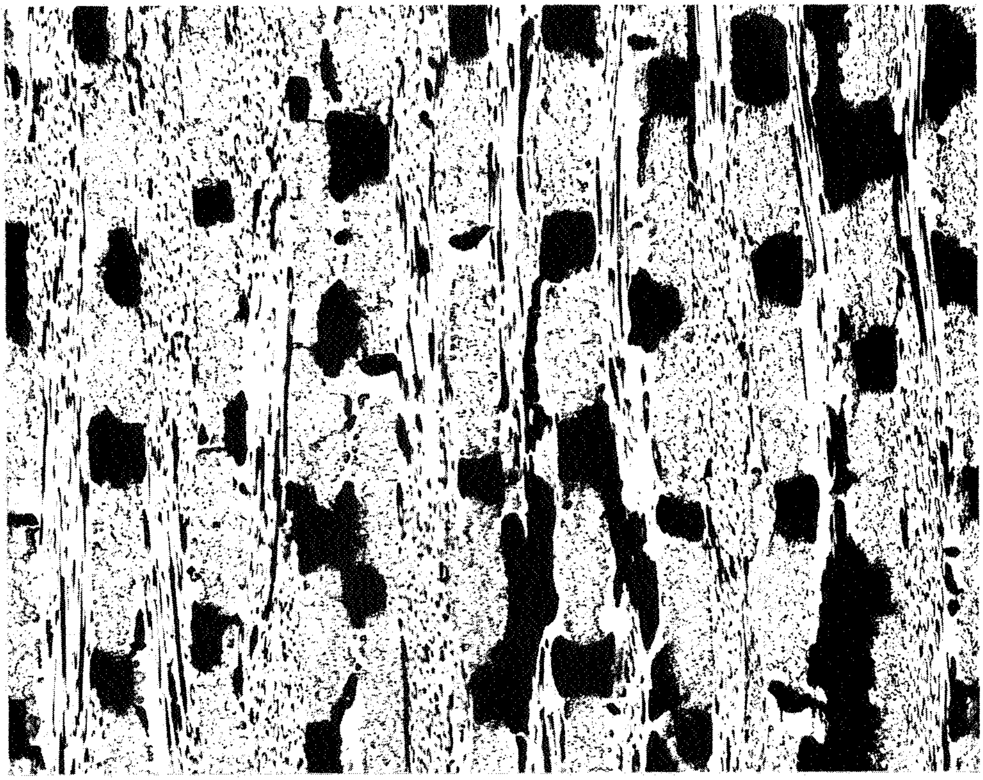
b. Phenolic-Epoxy Impregnations

The preliminary impregnation experiments with phenolic resins were unable to produce composites with less than 15- to 20-percent voids instead of the anticipated level of less than 10 percent. Despite this, it was decided that a partial phenolic impregnation would still be superior to all epoxy in performance characteristics, because of the higher char density from the phenolic.

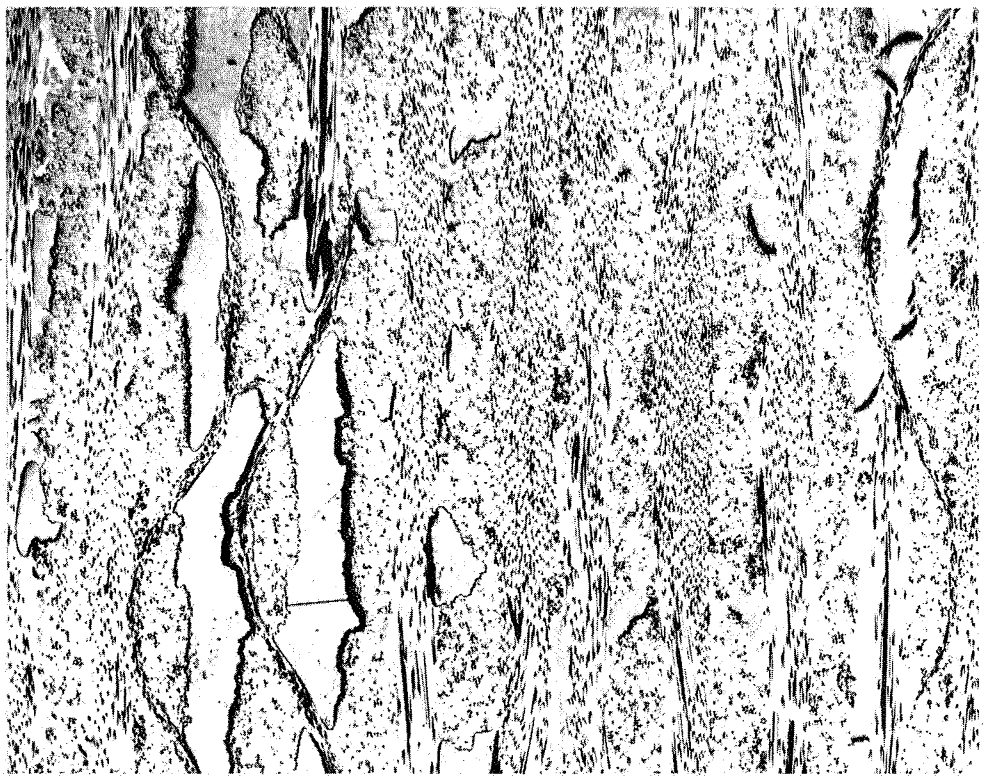
On this basis, all of the materials that had been impregnated with phenolic were re-impregnated with a low-viscosity charring epoxy novolac-based resin system to determine the effectiveness of re-impregnation.

Results both of the phenolic and the phenolic-epoxy impregnated materials are compared in Table XI. As further evidence of the effectiveness of impregnation, photos of cross sections taken at 30X on parts nos 874-40, 874-82, and 874-74(32) are shown in Figures 68 to 70.

The photos shown can be interpreted as follows:



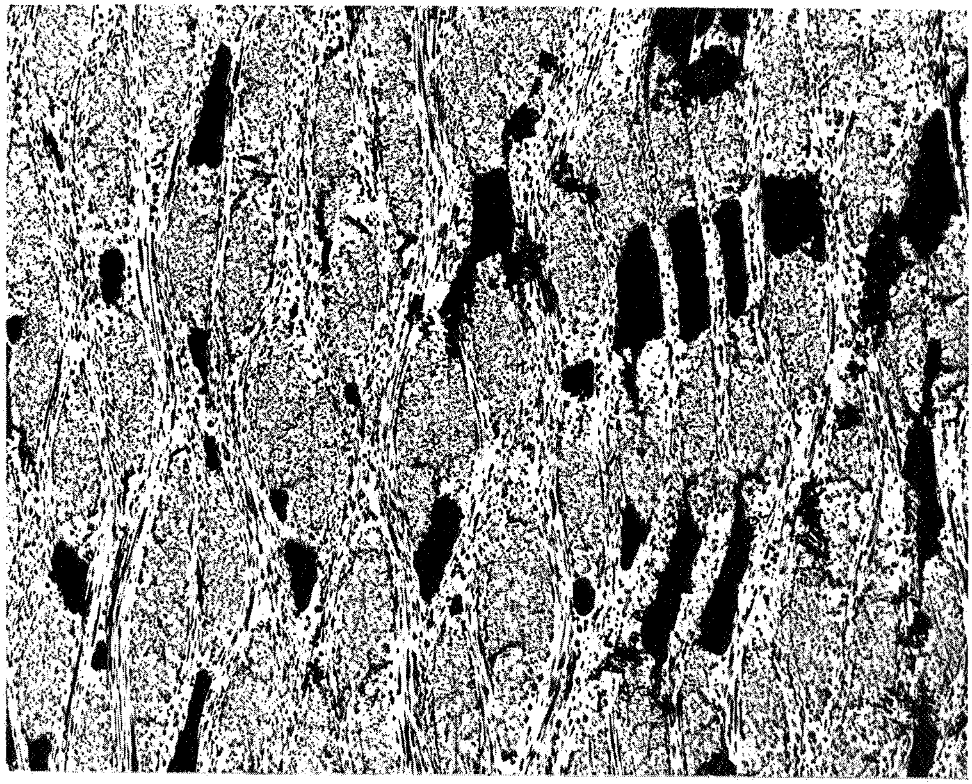
30 X MAGNIFCATION NO. 874-40 PHENOLIC IMPREGNATION



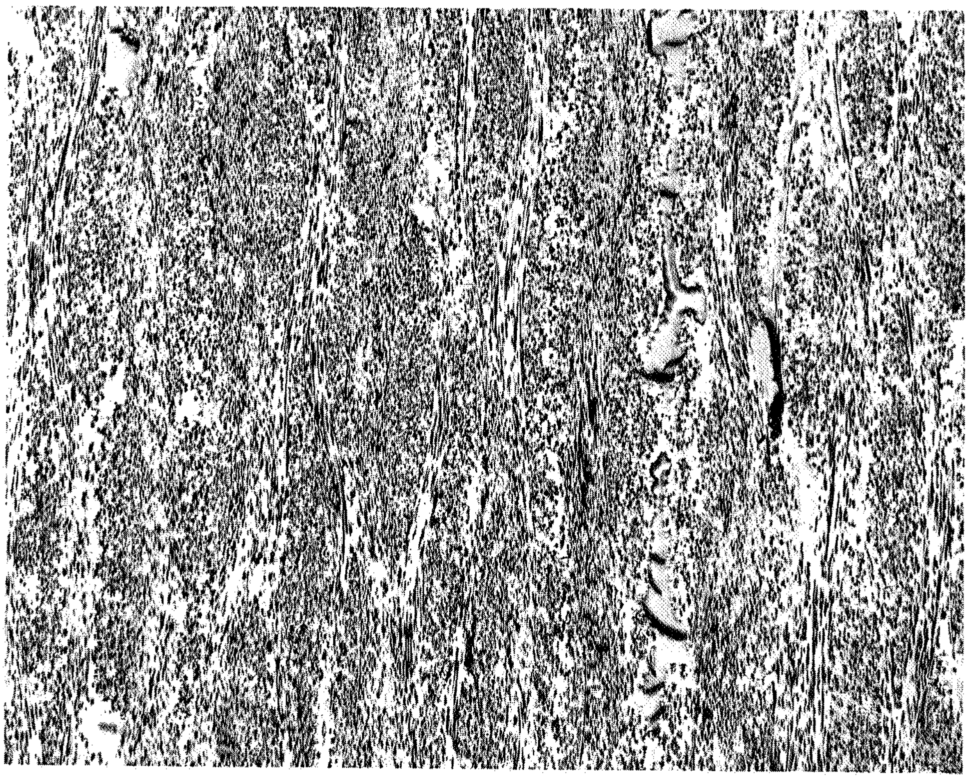
30 X MAGNIFICATION NO. 874-40 PHENOLIC-EPOXY IMPREGNATION

86-2124

Figure 68 CROSS-SECTION PHOTOGRAPHS OF PHENOLIC AND PHENOLIC-EPOXY IMPREGNATED LAMINATE (874-40)



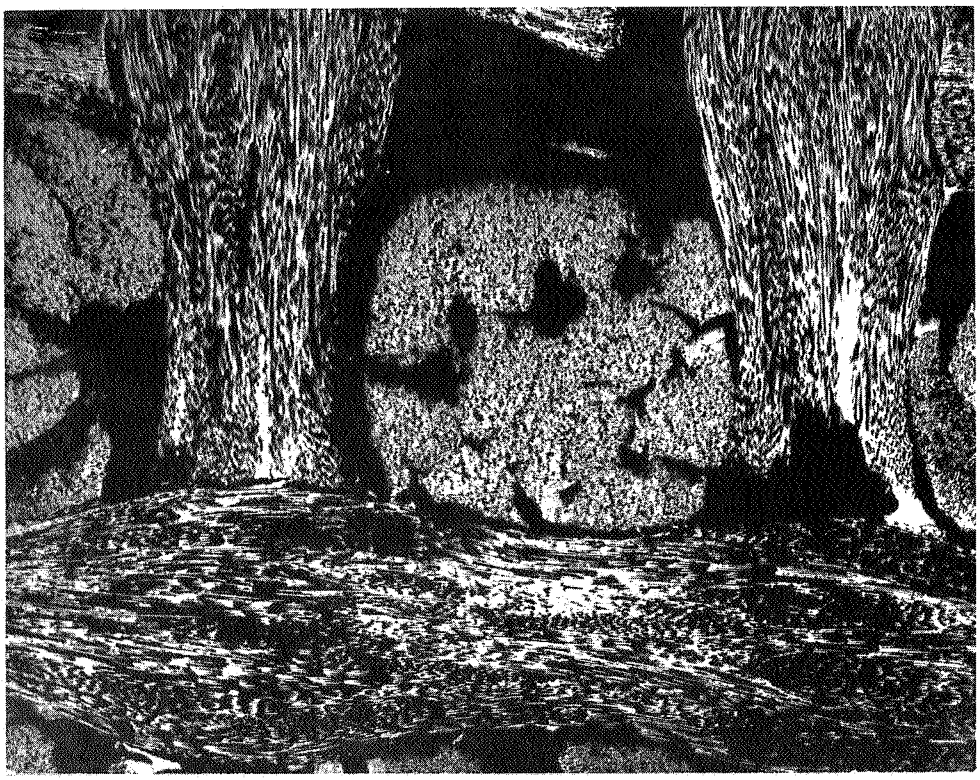
30 X MAGNIFICATION NO. 874-82 PHENOLIC IMPREGNATION



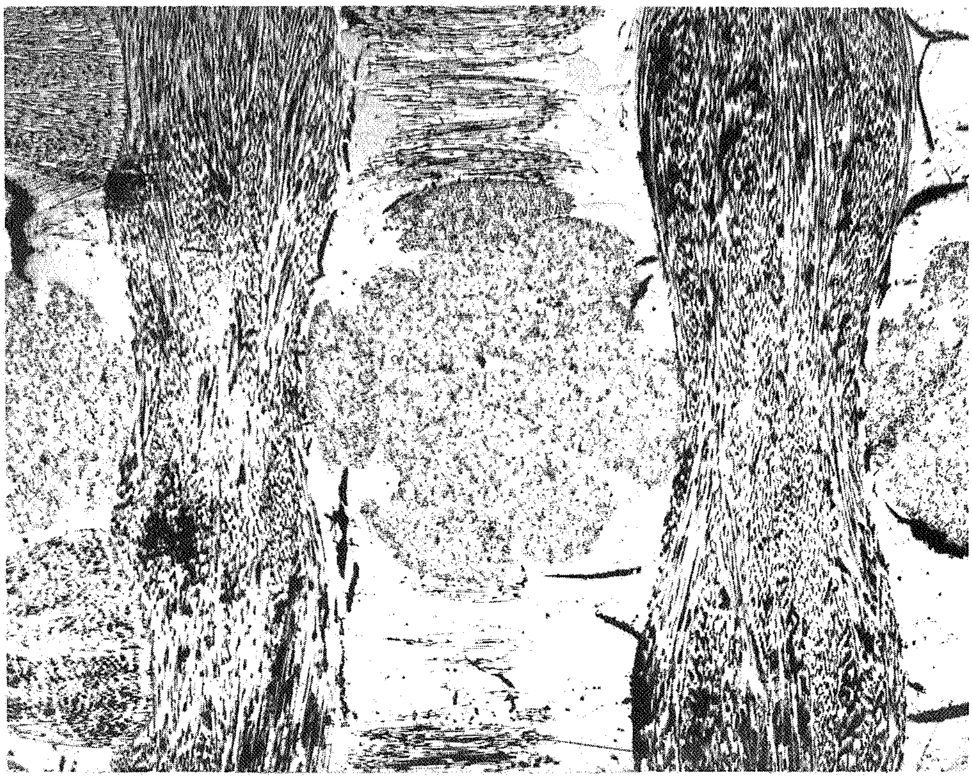
30 X MAGNIFICATION PHENOLIC-EPOXY IMPREGNATION

86-2125

Figure 69 CROSS-SECTION PHOTOGRAPHS OF PHENOLIC AND PHENOLIC-EPOXY IMPREGNATED LAMINATE (874-82)



30 X MAGNIFICATION NO. 874-74(32) PHENOLIC IMPREGNATION



30 X MAGNIFICATION NO. 874-74(32) PHENOLIC-EPOXY IMPREGNATION

86-2 **I26**

Figure 70 CROSSSECTION PHOTOGRAPHS OF PHENOLIC AND PHENOLIC-EPOXY IMPREGNATED AVCO 3-D (874-74) (32)

Color	
Black	voids
Light Gray	fibers
White	phenolic resin (barely visible)
Medium Gray	epoxy resin

Since the results of this work were considered significant in terms of achieving a good portion of the goals established at the onset of the program, it was then decided to compare the mechanical behavior of 3-D material impregnated in this manner for comparison with Avco 3-D epoxy impregnated material.

The method chosen to impregnate with phenolic was similar to that used for sample No. 874-86(41). A 3- x 3- x 4-1/2-inch billet of 3-D was impregnated with phenolic. After the phenolic impregnation, a portion (1/3) of the material was sectioned for evaluation in the phenolic impregnated condition, and the remaining (2/3) section of material was then re-impregnated with epoxy for evaluation in the phenolic-epoxy condition. The physical and mechanical properties of each section have been determined. The data obtained on these materials plus previous data generated on Avco 3-D epoxy material are presented for comparison in Table XII.

4. Discussion of Results

Impregnation studies were initiated with an epoxy system to speed up the transition between sample procurement and physical testing. Complete impregnation was difficult, but not impossible, to obtain with this medium viscosity resin system. Vacuum impregnation and vacuum impregnation followed by cyclical pressurization gave proper density composites. Work, however, with a low-viscosity epoxy system was shown to be more efficient. The strong effect of viscosity follows over into the phenolic impregnation studies, where the complication of volatile evolution during cure is added. The porosity resulting from this volatile production was eliminated by re-impregnation with a low viscosity charring epoxy resin system. This re-impregnation to eliminate voids showed a 10-percent improvement in tensile strength for Avco 3-D fabric reinforced composite. A 100-percent phenolic impregnation would be more desirable from the ablation point of view since the phenolics give a much denser char, and are, therefore, presumably stronger. Further, the effect of curing pressure on the phenolic system has not been used to best advantage in our present impregnation system. Effective utilization of these parameters required development time beyond the limitations of this contract. Poor impregnation was a problem with the epoxy system when the reinforcement fabric was very open. Here the interaction between the small reinforcement concentration and the resin shrinkage from cure caused serious cracking. This problem was also overcome by re-impregnation with epoxy. Suprisingly the thermal shock properties of the two composites, re-impregnated and not re-impregnated, were apparently the same, though the physical properties of the re-impregnated composite were superior.

TABLE XII

COMPARISON OF THE PHYSICAL AND MECHANICAL CHARACTERISTICS OF PHENOLIC, PHENOLIC-EPOXY, AND EPOXY-IMPREGNATED AVCO 3-D

Material Composition	No. 909-1 (48-1) S-Glass/ Phenolic	No. 909-1 (48-2) S-Glass/ Phenolic Epoxy	No. 874-5 (26) S-Glass/ Epoxy
Physical Properties			
ıl : Density (g/cm^3	1.77	1.90	1.80
ı ı Density ı ı m	1.37	1.38	1.36
l O & Closed Porosity (percent)	13.5	3.5	----
)pen '(osity (percent)*	11.6	1.6	----
] : iı Content (percent)	22.6	27.4	28.0
Theoretical ısity (ı ')	1.94	1.94	----
Densification Effici n (percent)	91.2	97.7	----
Impregnation Effici ı :ȝ (percent)	70.0	92.2	----
Mechanical Properties** ertical Yarns - Z axis			
Prop. L r (psi)	4050	4950	2200
Yield Stress (psi)	17050	23400	----
Tensile Stre ›si)	33000	41700	38200
Elastic Modulus x 10^{-6} (psi)	2.50	2.65	2.68
Total Strain (percent)	2.13	2.38	3.18

* As measured in air pycnometer

** Values are average of two tests

C. MECHANICAL AND THERMAL EVALUATION

1. Introduction

The mechanical and the thermal evaluation were approached from three directions. To the empirical determination of mechanical and thermal properties has been added the comparison of these properties to those predicted by anisotropic elasticity theory. The specific empirical data are necessary to make a valid quantitative comparison of the various candidate materials. These data, however, are inherently very specific, and extrapolation to other reinforcements, different geometries, and various resins systems can be hazardous. Should, however, the materials shown be represented by anisotropic elasticity theory, then the extrapolations would be much more reliable, and design work based on the physical and thermal property data would predict behavior close to that exhibited in performance tests.

The billets made by impregnating the candidate fabrics were machined into specimens for tensile, compression, shear (torsion and notched bar), thermal-expansion, and thermal-shock testing wherever possible. Some fabric samples were too small for a complete set of test specimens, in which case emphasis was placed on shear and interlaminar properties as the most critical. Most of the candidate fabrics were very thin relative to the other dimensions, so that tensile properties in the interlaminar direction were obtained from butt-tensile samples. The description of the sample geometry is discussed later in this section. Since the mechanical properties of a composite are a strong function of the reinforcement content, the comparison of the candidate composites will have to be made cautiously, as most of the fabrics could not be woven as densely as the equivalent reference laminates. Several of the needled samples were impregnated by molding to get the higher density, but this modified the fabric geometry, and some of the interlaminar mechanical properties suffered, as will be discussed later in this section.

This section then is divided into three parts: The first part describes the anisotropic elasticity theory in terms of the moduli variation with direction of stress, thermoelastic behavior, and yield criterion and discusses the relevance of this theory to the test data; the second part compares the candidate composites on the basis of the empirical test data; and the third part describes the thermal shock tests and results.

2. Discussion of Anisotropic Elasticity Theory

a. Moduli Variation

Typical structure of the various types of fabric
and it is apparent that the assumption of isotropy in any particular plane

is an idealization. To a certain extent, however, anisotropic elasticity theories can be applied to reinforced plastics. Application of existing theories for predicting moduli, strength, and thermal expansion behavior was previously considered.[1] In that report departures from mathematical idealization due to non-linear stress-strain response, high-strain rate effects, and high-heating-rate-induced irreversible chemical changes were indicated. Over a modest range of temperatures, however, anisotropic elasticity can be applied to represent the mechanical behavior of the plastic composites. To this end, a very brief review of the appropriate formulas is now presented, and then the structure of the theory is used in conjunction with observed mechanical behavior to compare and assess the potential of the different materials considered.

If, in first approximation, the reinforced plastic may be considered to be transversely isotropic, it would then follow that the gross behavior of any representative volume element would obey the thermoelastic stress-strain laws of plane isotropy:

$$\epsilon_1 = \frac{\sigma_1}{E_1} - \frac{\nu_{21}}{E_1}(\sigma_2 + \sigma_3) + \alpha_1 T \qquad (3.1)$$

$$\epsilon_2 = -\frac{\nu_{21}}{E_1}\sigma_1 + \frac{\sigma_2}{E_2} - \frac{\nu_2 \sigma_3}{E_2} + \alpha_2 T \qquad (3.2)$$

$$\epsilon_3 = -\frac{\nu_{21}\sigma_1}{E_1} - \frac{\nu_2 \sigma_2}{E_2} + \frac{\sigma_3}{E_2} + \alpha_2 T \qquad (3.3)$$

$$\gamma_{12} = \frac{\tau_{12}}{G_{12}} \qquad (3.4)$$

$$\gamma_{13} = \frac{\tau_{13}}{G_{12}} \qquad (3.5)$$

$$\gamma_{23} = \frac{\tau_{23}}{G_{12}} = \frac{2(1+\nu_2)}{E_2}\tau_{23}, \qquad (3.6)$$

where the coordinate system is chosen in the warp and fill directions, and the axis perpendicular to the weave. The independent elastic constants are

E_1, E_2	= Uniaxial Moduli
α_1, α_2	= Coefficient of Thermal Expansion
G_{12}	= Shear Modulus
ν_{21}, ν_2	= Poisson's Ratio,

where

$$\nu_{21} = \frac{|\epsilon_2|}{|\epsilon_1|} \qquad \text{for uniaxial tests in } X_1 \text{ direction,}$$

and

ν_2 relates strains at right angles in the X_2, X_3 plane.

The three dimensionally reinforced epoxy resin system is essentially a balanced construction of approximately 2000 yarns per square inch in three orthogonal directions. (Each yarn can sustain $\approx$ 19.9 lb.) When the idealization of an orthotropic continuum is applied, the principal elastic constants are E_1, E_2, and E_3 (uniaxial moduli); G_{23}, G_{13}, and G_{12} (shear moduli); and ν_{12}, ν_{21}, ν_{13}, ν_{31}, ν_{23}, and ν_{32} (the Poisson coefficients).

The correctness and accuracy of the assumed forms of anisotropy must be established. This can be easily accomplished by applying elementary tensor transformation laws to predict elastic constant variation and by comparing theoretical and experimental observations. This has been done wherever sufficient data were available.

Refering to Leknitskii[2], one obtains for the uniaxial modulus

$$\frac{1}{E_1'} = \frac{\cos^4\theta}{E_1} + \left(\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_1}\right)\sin^2\theta\cos^2\theta + \frac{\sin^4\theta}{E_2}, \qquad (3.7)$$

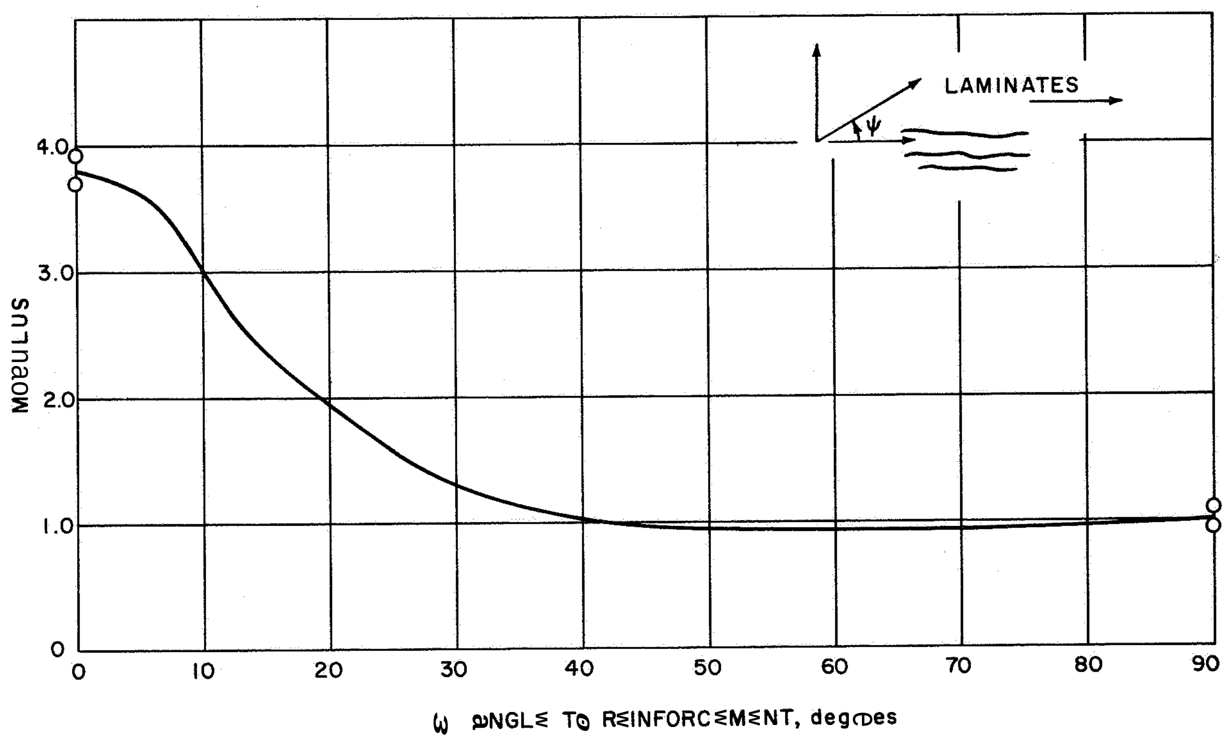
for the shear modulus

$$\frac{1}{G_{12}'} = \frac{1}{G_{12}} + 4\left(\frac{1}{E_1} + \frac{1}{E_2} + \frac{2\nu_{12}}{E_1} - \frac{1}{G_{12}}\right)\sin^2\theta\cos^2\theta, \qquad (3.8)$$

and for the Poisson coefficient ν_{12}.

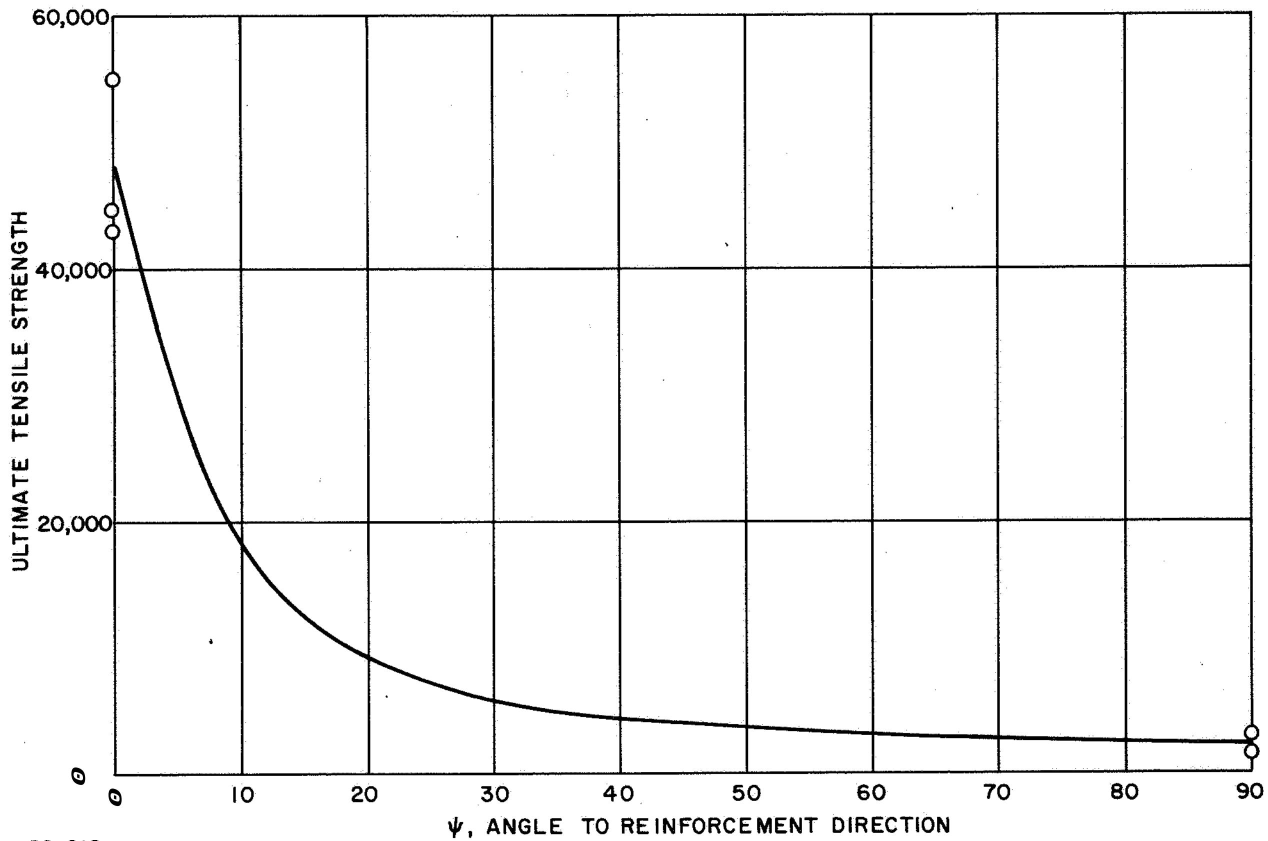
$$\frac{\nu_{12}'}{E_2'} = \left(\frac{1}{E_1} + \frac{1}{E_2} + \frac{2\nu_{12}}{E_1} - \frac{1}{G_{12}}\right)\sin^2\theta\cos^2\theta - \frac{\nu_{12}}{E_1}. \qquad (3.9)$$

Comparison of the observed mechanical behavior of the laminated re-inforced epoxy, the three dimensionally glass filament reinforced epoxy, and the needled matt fabric to predictions based on equations (3.7) through (3.9) is made in Figures 71 through 83.



86-Z127

Figure 71 TENSILE-MODULUS VARIATION FOR GLASS-EPOXY REFERENCE LAMINATE (874-76)



86-2123

Figure 72 ULTIMATE TENSILE-STRENGTH VARIATION FOR GLASS-EPOXY LAMINATE (874-76)

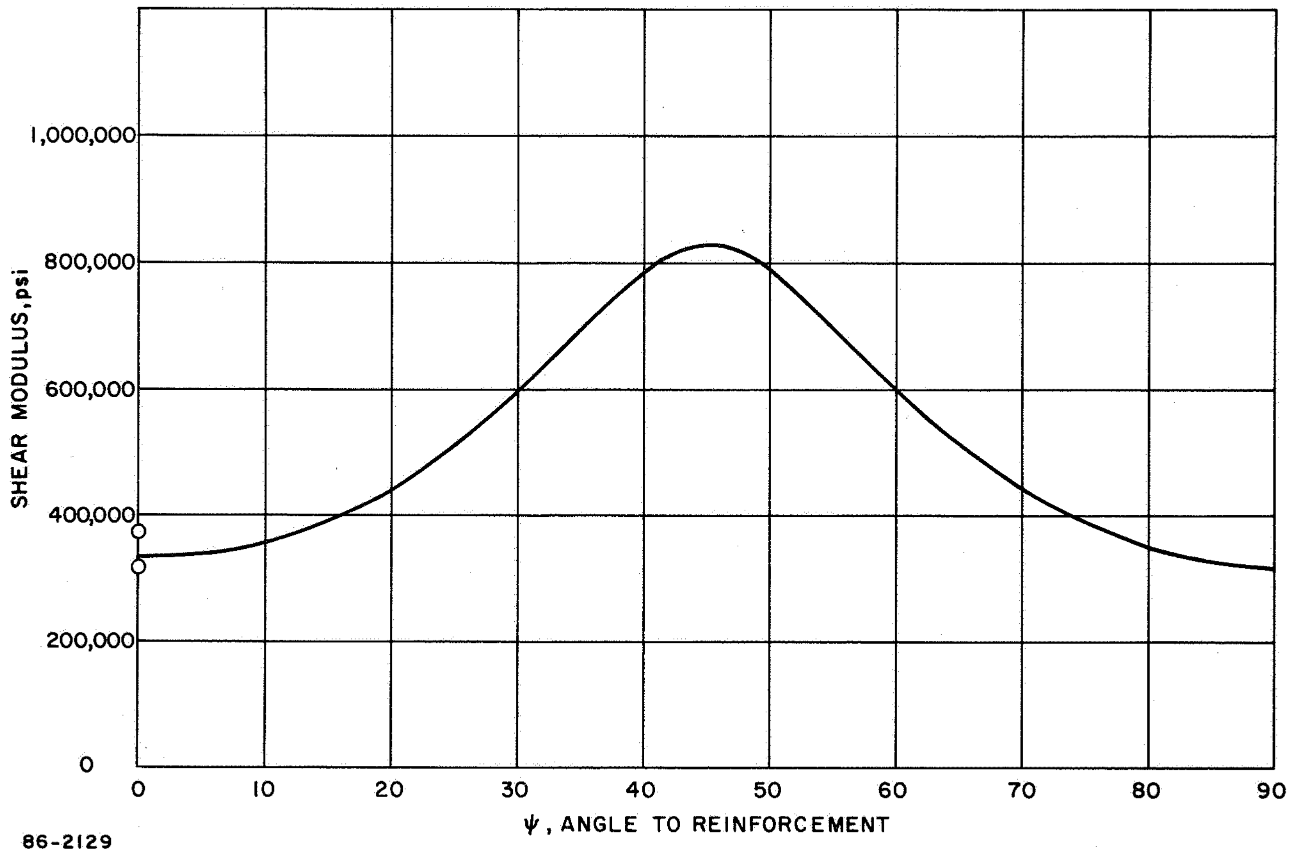


Figure 73 SHEAR-MODULUS VARIATION FOR GLASS-EPOXY REFERENCE LAMINATE (874-76)

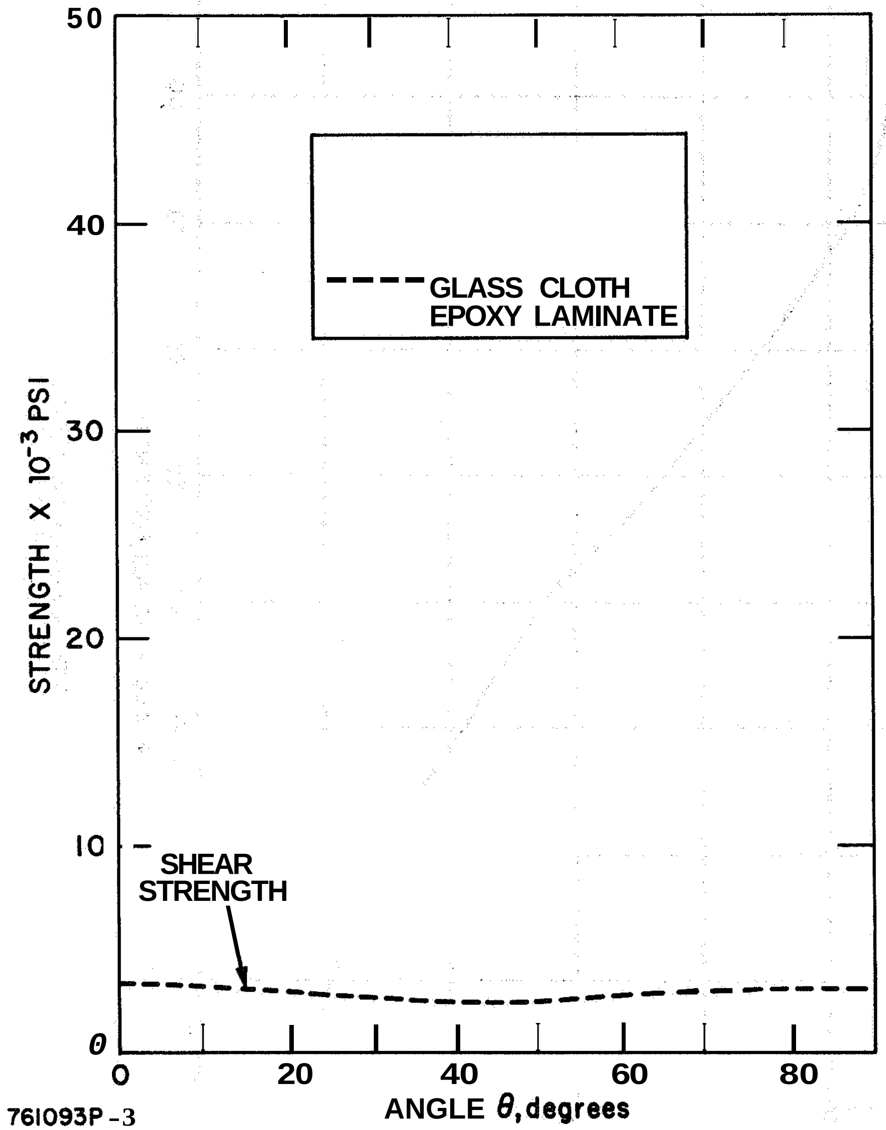


Figure 74 SHEAR-STRENGTH VARIATION FOR GLASSEPOXY REFERENCE LAMINATE (874-76)

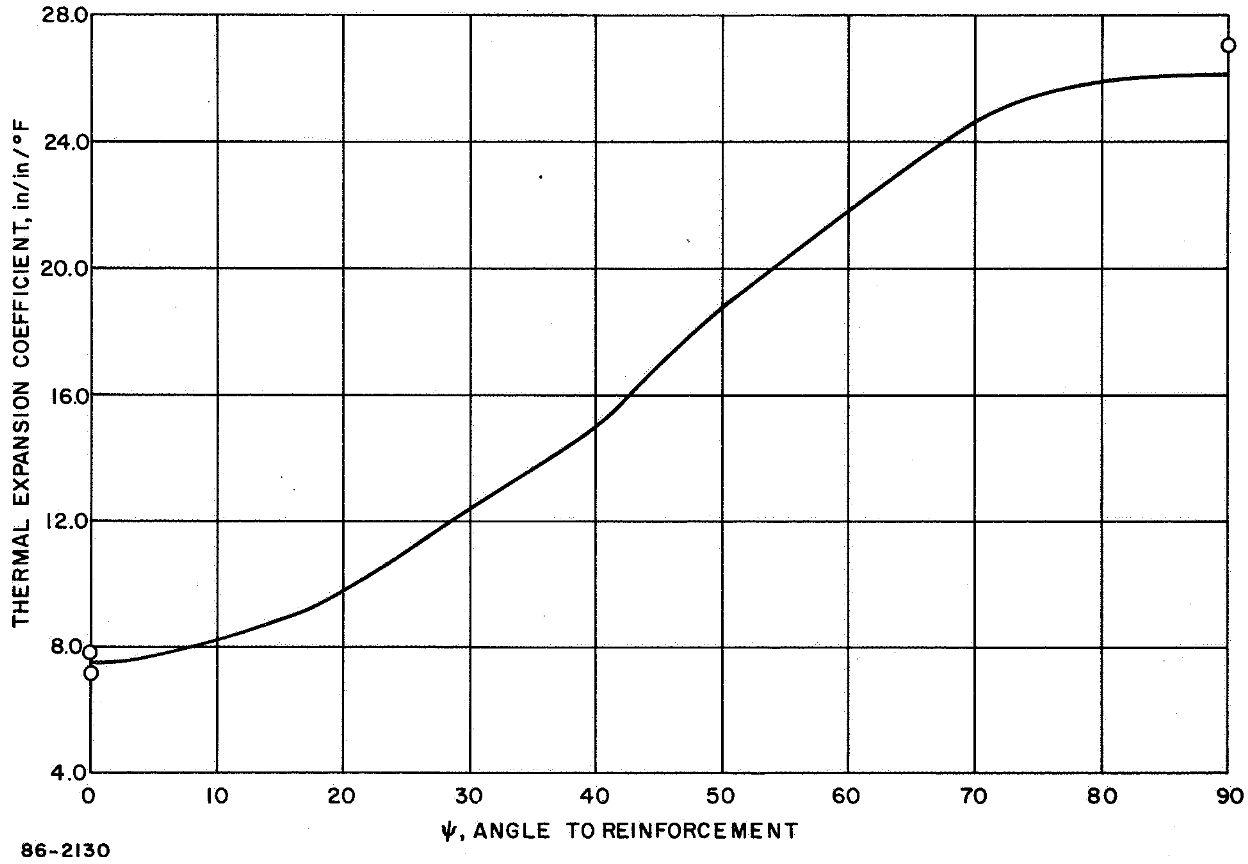
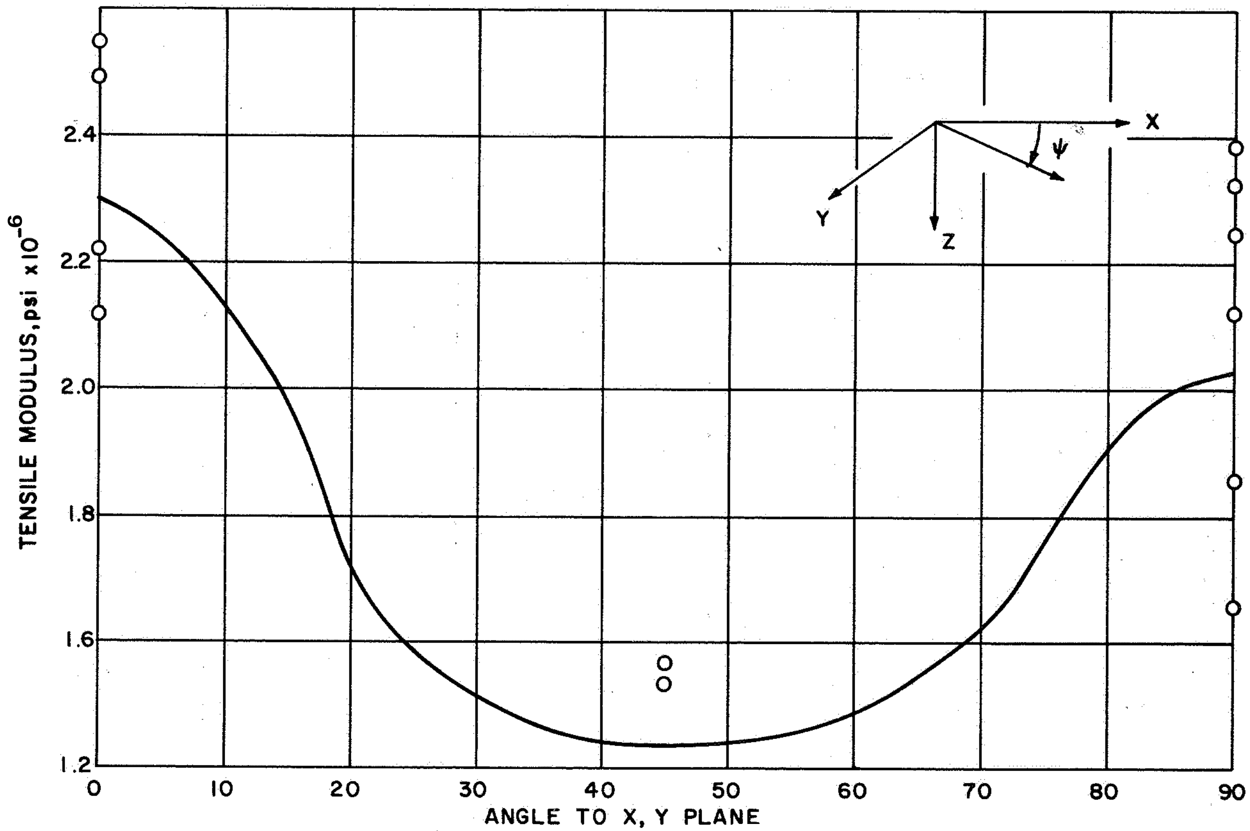


Figure 75 COEFFICIENT OF THERMAL-EXPANSION VARIATION FOR GLASS-EPOXY REFERENCE LAMINATE (874-76)



86-2131

Fig. 76 TENSILE-MODULUS VARIATION FOR AVCO 3-D EPOXY

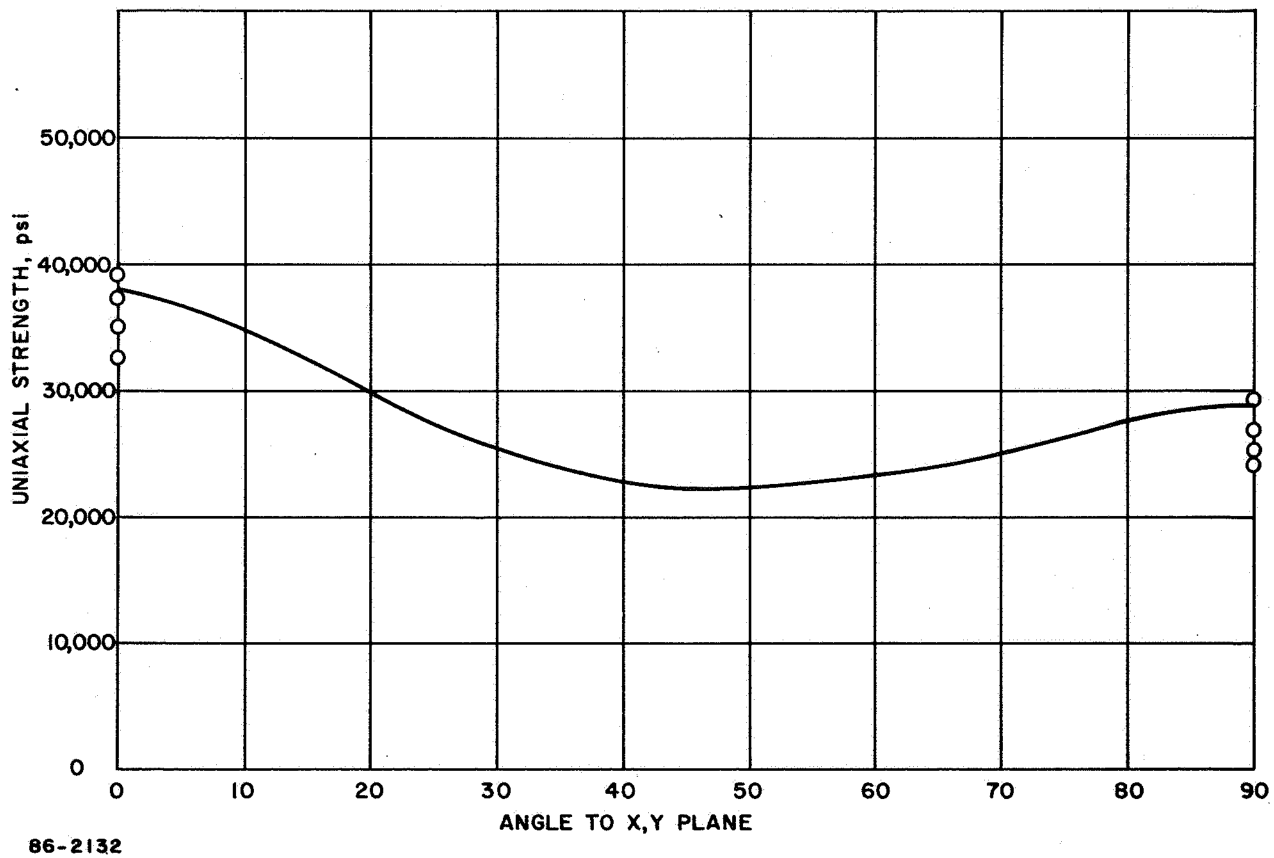


Figure 77 ULTIMATE TENSILE-STRENGTH VARIATION FOR AVCO 3-D EPOXY

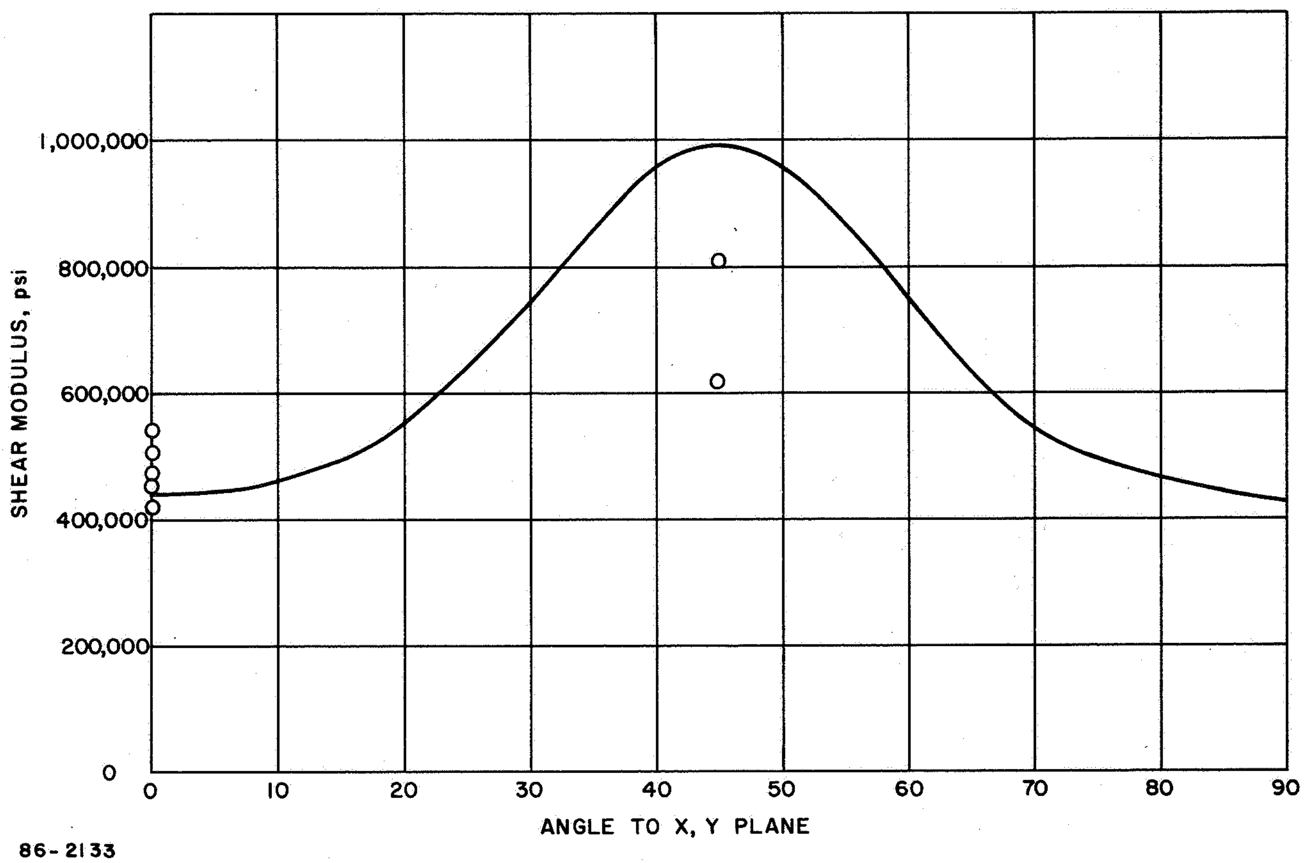


Figure 78 SHEAR-MODULUS VARIATION FOR AVCO 3-D EPOXY

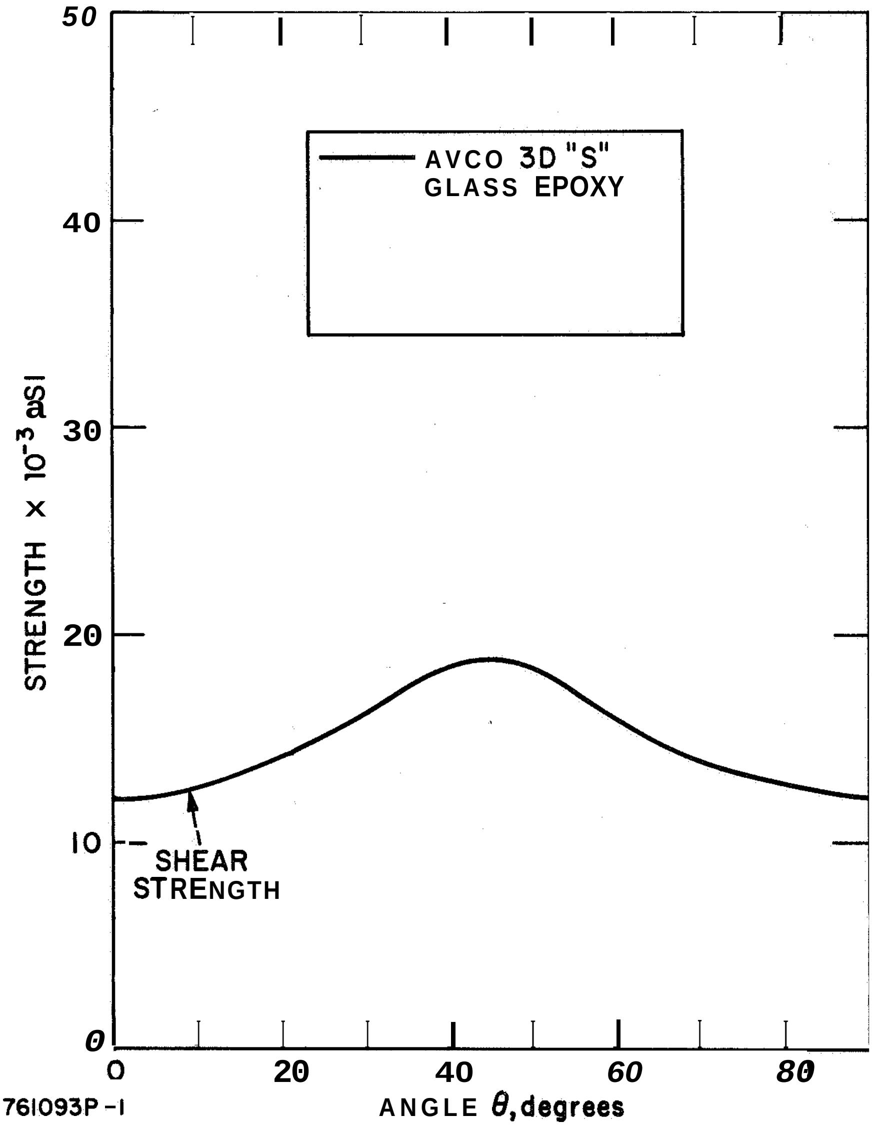
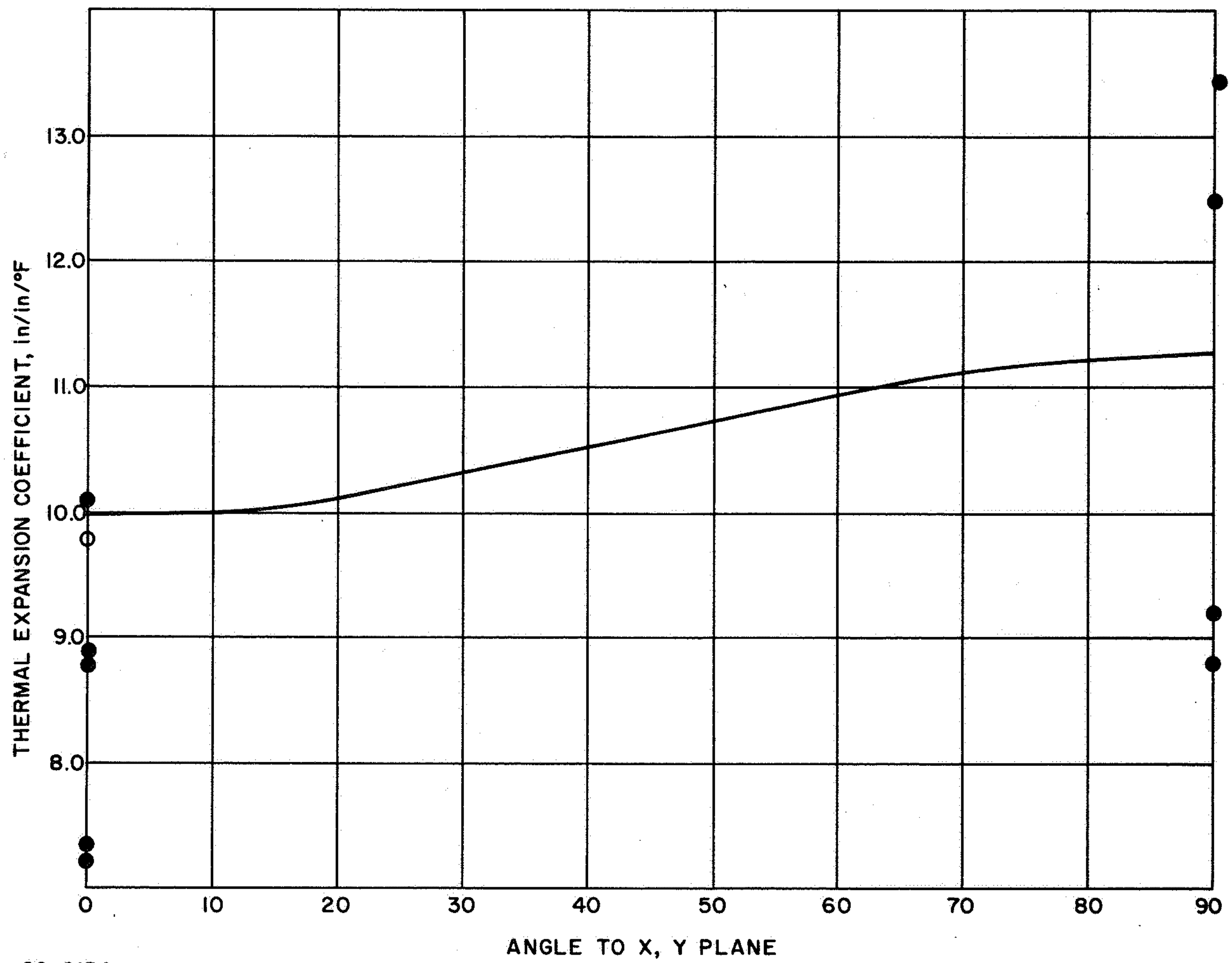


Figure 79 SHEAR-STRENGTH VARIATION FOR AVCO 3-D EPOXY



86-2134

Figure 80 COEFFICIENT OF THERMAL-EXPANSION VARIATION FOR AVCO 3-D EPOXY

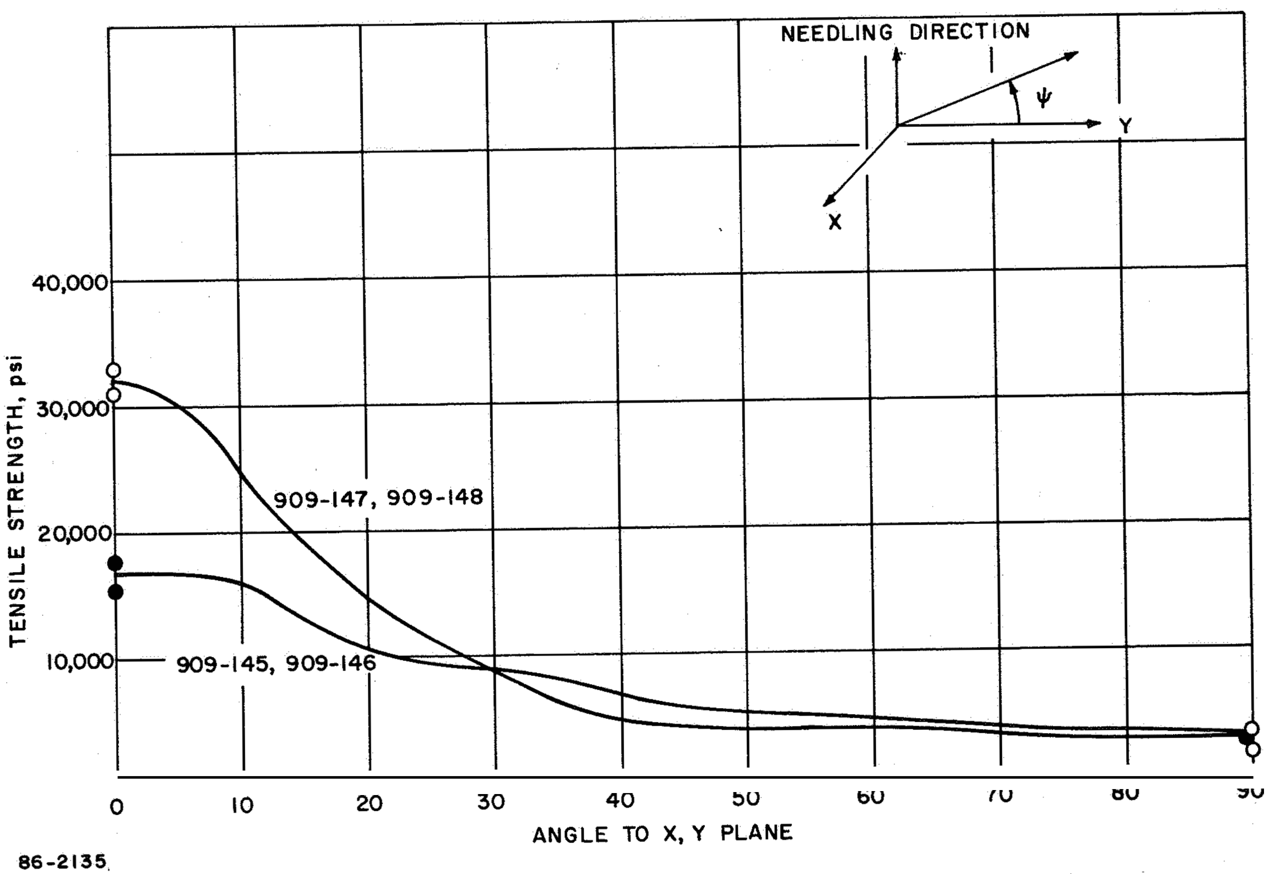
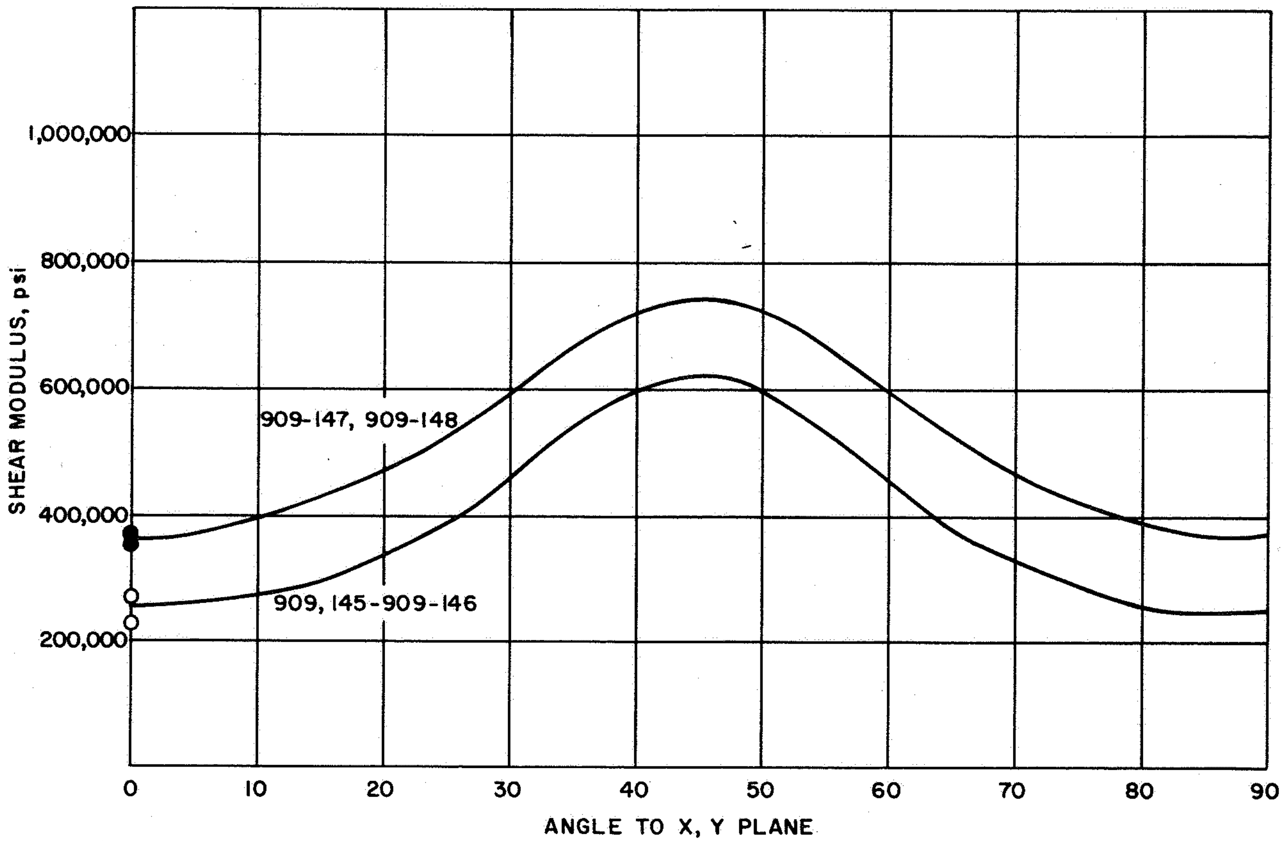


Figure 81 TENSILE-STRENGTH VARIATION FOR NEEDLED FABRIC MATT-EPOXY



86-2136

Figure 82 SHEAR-MODULUS VARIATION FOR NEEDLED FABRIC MATT-EPOXY

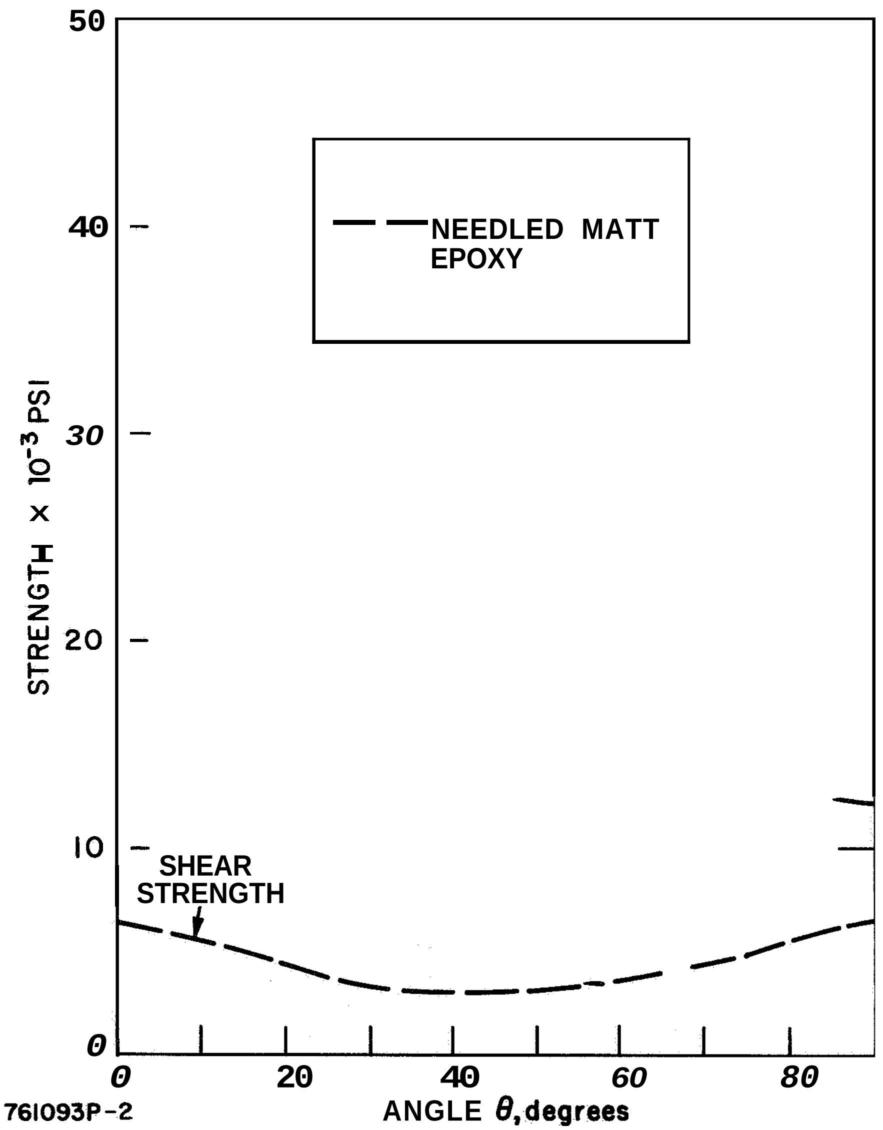


Figure 83 SHEAR-STRENGTH VARIATION FOR NEEDLED FABRIC MATT-EPOXY

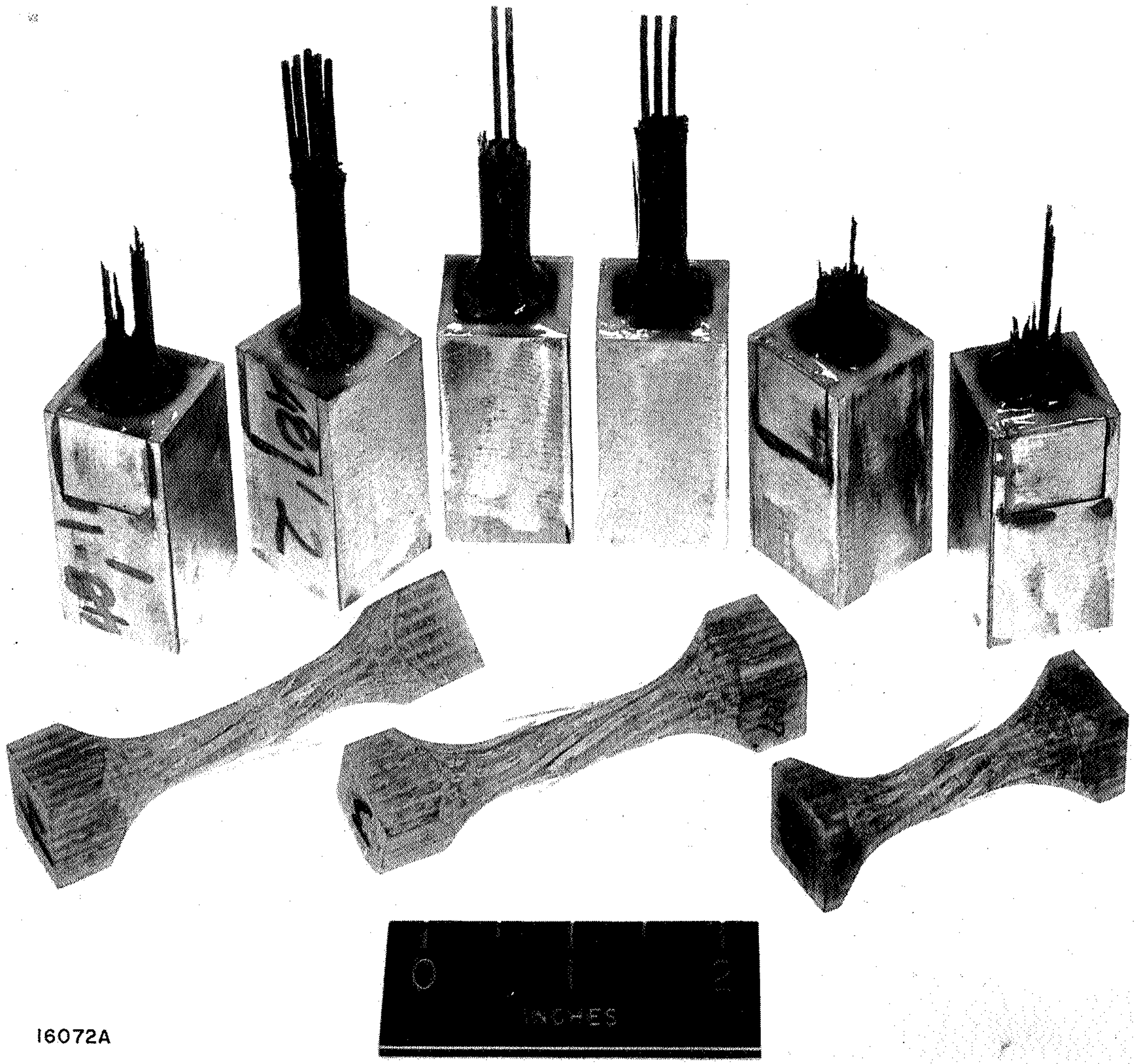


Figure84 TYPICAL TORSION AND TENSILE SAMPLES FOR AVCO 3-D

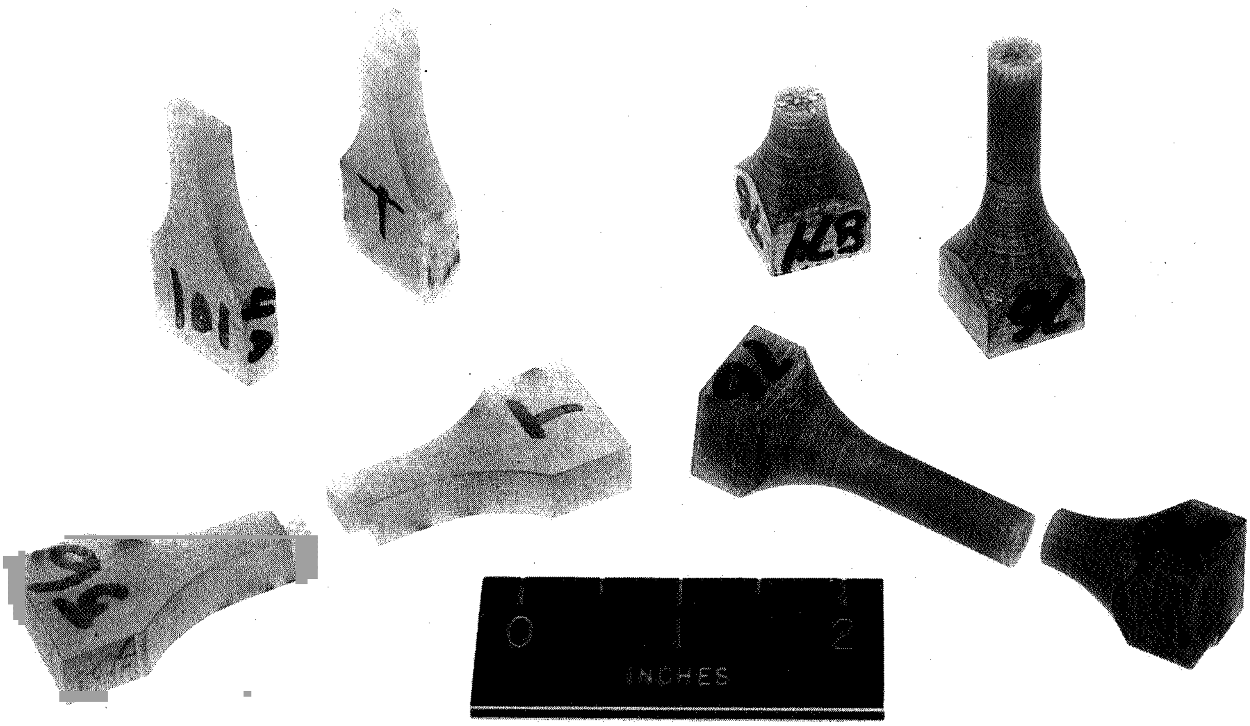


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Figure 85 TYPICAL SAMPLES FOR REFERENCE GLASS-EPOXY LAMINATE

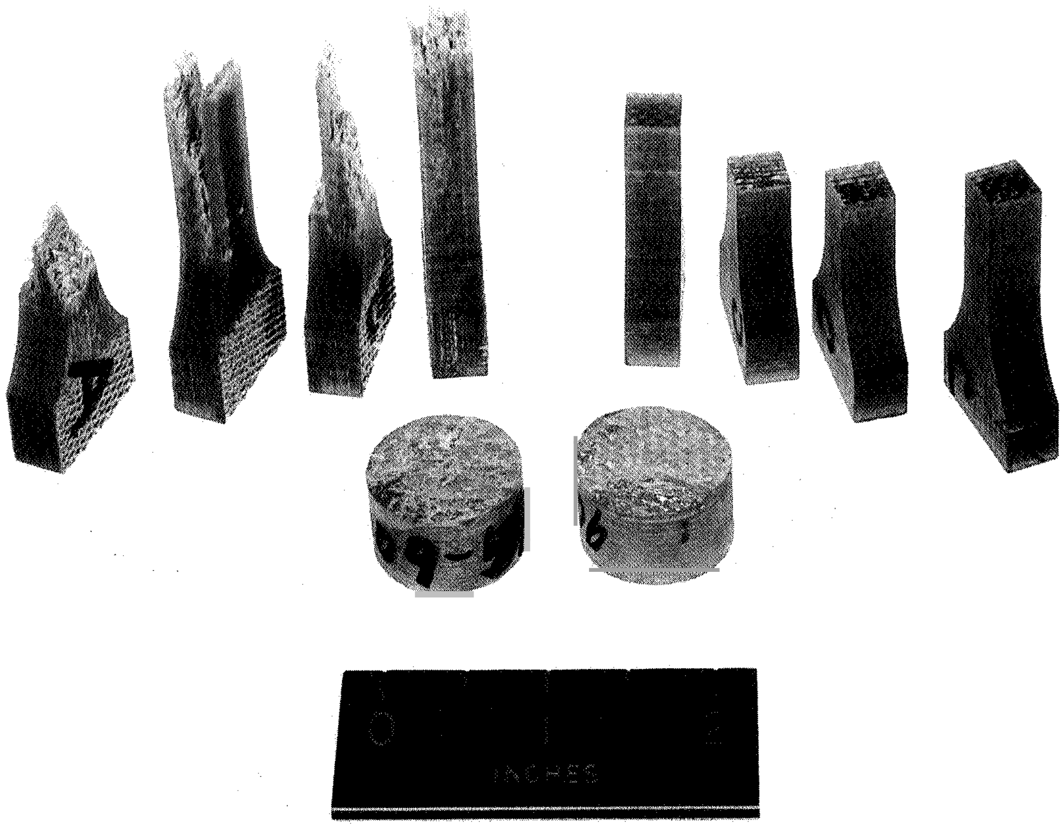

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Figure 56a TYPICAL SAMPLES FOR NEEDLED MATT SAMPLES

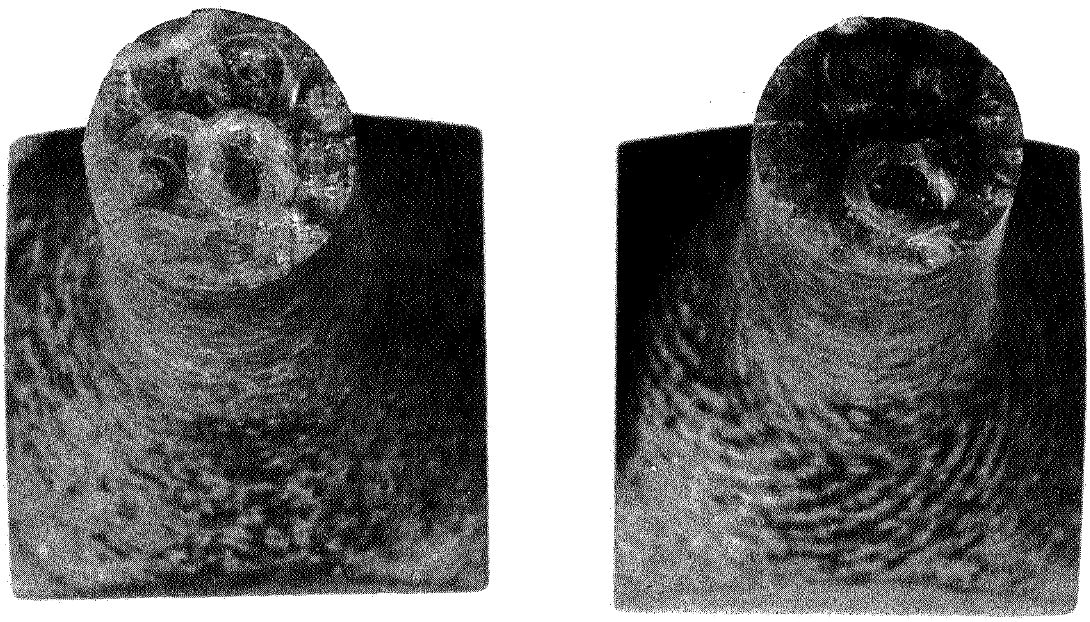

Figure 86b TYPICAL SAMPLE OF DOUBLE LOOP FABRIC LAMINATE

b. Thermoelastic Behavior

Greszczuk[3] has utilized the thermoelastic equations for an orthotropic material in thermal problems encountered in composite plastics. According to his approach, three thermal properties are required to completely specify the behavior of the material: Two coefficients of thermal expansion, related to deformations in two perpendicular directions, and a third coefficient associated with thermally induced shear deformation. Applying elementary transformation of the coordinate axis, Greszczuk obtained the following expressions for the thermal coefficients in the rotated coordinate system:

$$\alpha_1' = \alpha_2 \sin^2 \theta + \alpha_1 \cos^2 \theta \qquad (3.10)$$

$$\alpha_2' = \alpha_2 \cos^2 \theta + \alpha_1 \sin^2 \theta \qquad (3.11)$$

$$\alpha_{12}' = 2(\alpha_2 - \alpha_1) \sin\theta \cos\theta \ , \qquad (3.12)$$

where the coordinate scheme of described after Equation **(3.6)** is appropriate.

Equation (3. 10) was seen to accurately predict the thermal strain characteristics both of graphite and silica phenolic laminates, for the temperatures ranging from -65" to 150" F and -65 to 200" F, respectively. At elevated temperatures, the thermal expansion properties are not linearly temperature dependent. Typically the thermal expansion curve for slow heating rates exhibits an inflection point with the coefficient of thermal expansion ultimately increasing at the highest temperatures. For restricted regions, however, these elementary transformation Equations (3. 10 through 3. 12) adequately predict the thermal behavior of the reinforced plastics.

The predicted and observed thermal expansion coefficient for the glass epoxy laminate, the Avco/RAD 3-D and needled matt constructions appears in Figures 87—89.

c. Anisotropic Yield Criterion

Thus far, the present investigation has been concerned with appropriate constitutive equations for the plastic composites. Now comparison of the observed strength characteristics of these materials with simplified yield criterion is made.

Hill[4] postulated that the yield conditions for anisotropic media is a quadratic function of the stress components

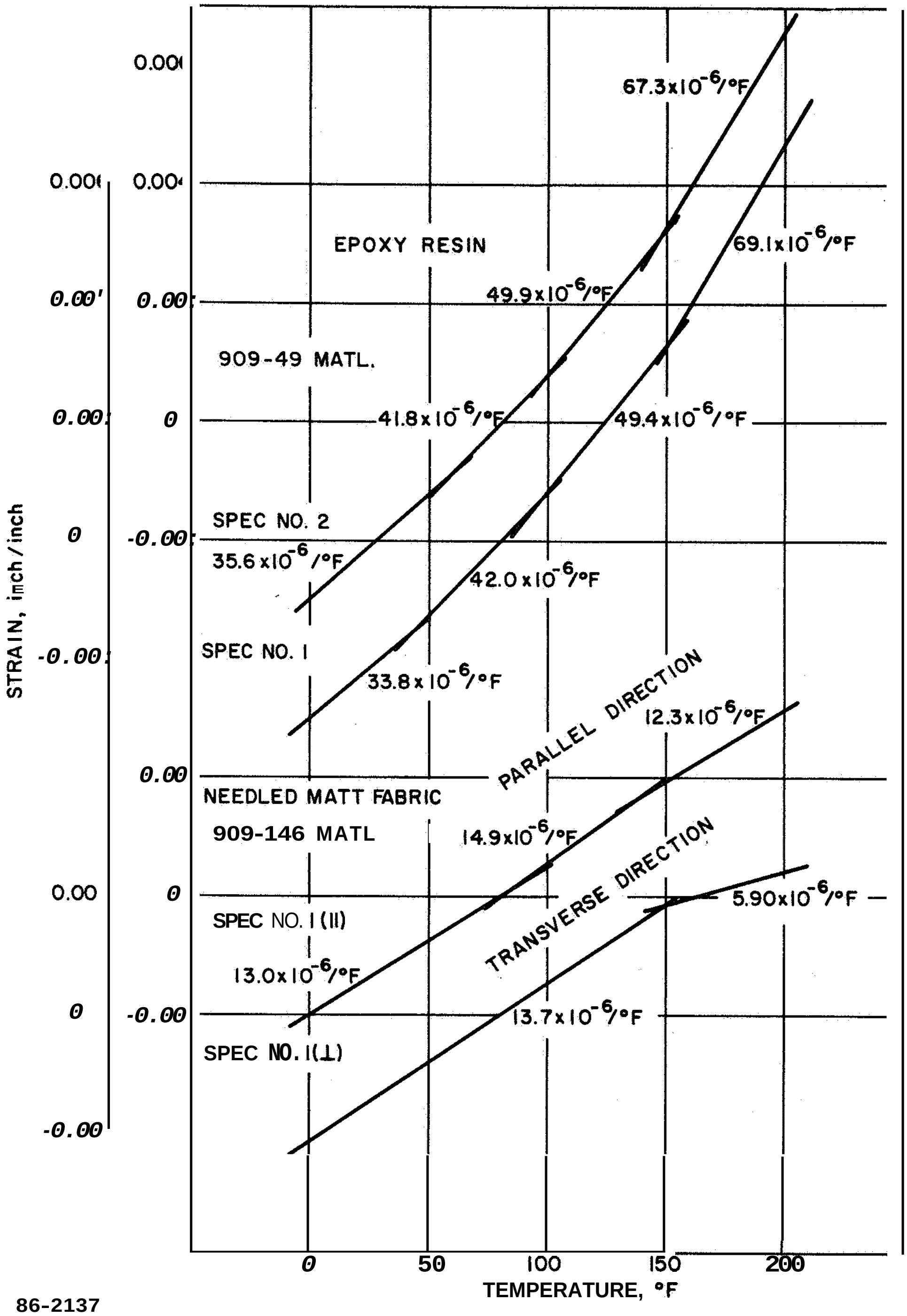

Figure 87 THERMAL STRAIN VERSUS TEMPERATURE FOR PURE RESIN AND NEEDLED FABRIC

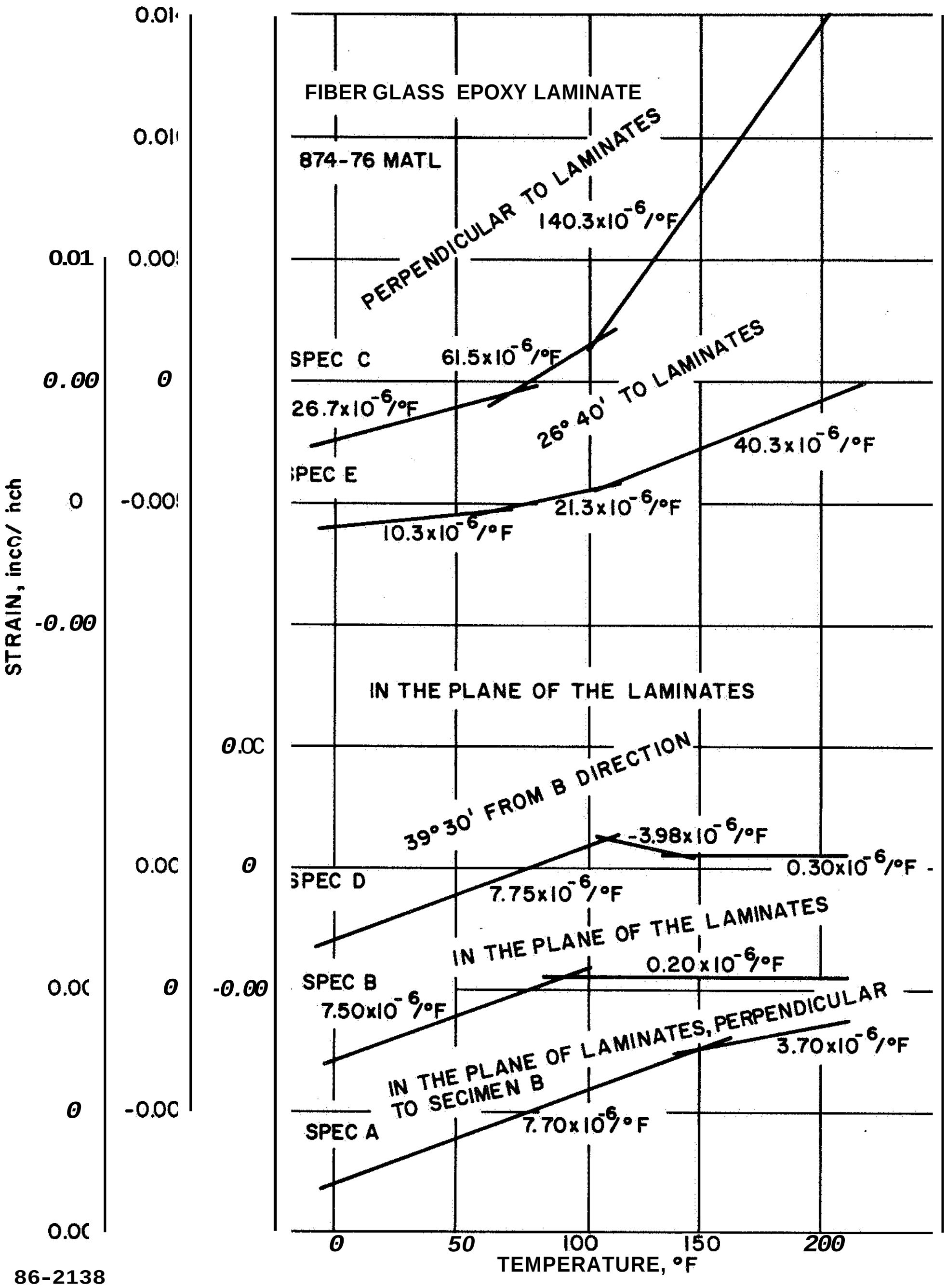

Figure 88 THERMAL STRAIN VERSUS TEMPERATURE FOR REFERENCE GLASS-EPOXY LAMINATE

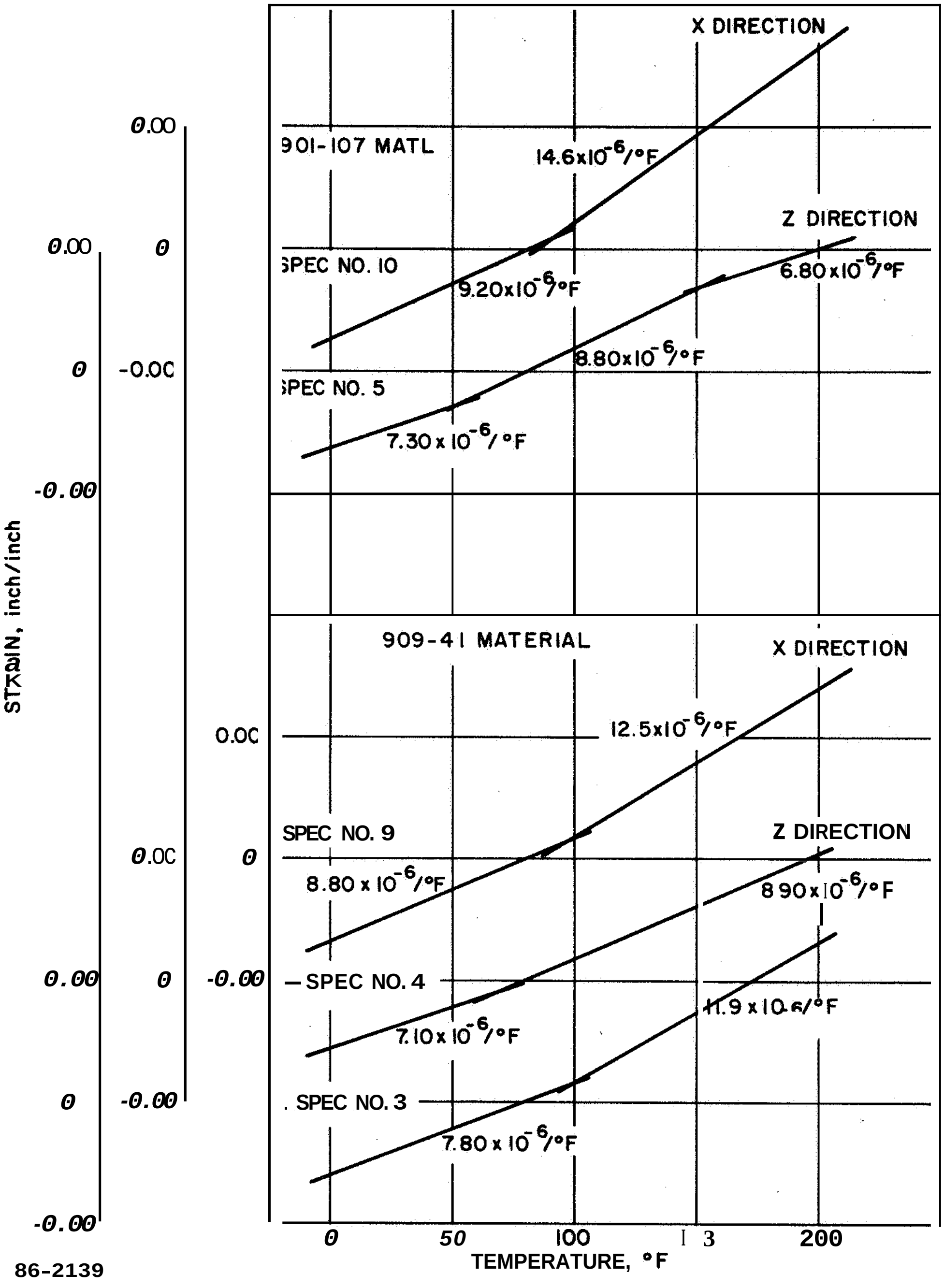

Figure 89 THERMAL STRAIN VERSUS TEMPERATURE FOR AVCO 3-D EPOXY COMPOSITE

$$2f(\sigma_{ij}) = F(\sigma_2 - \sigma_3)^2 + G(\sigma_3 - \sigma_1)^2 + H(\sigma_1 - \sigma_2)^2 \tag{3. 13}$$

$$+ 2L\ \tau_{23}^2 + 2M\tau_{31}^2 + 2N\tau_{12}^2 = 1,$$

where X_1, X_2, and X_3 are axes of material symmetry, and F, G, H, L, M, and N are material constants.

The strength of quasi-homogeneous anisotropic composites was reported by Azzi and Tsai.[5] One of the basic assumptions of their failure conditions is that there exist three mutually perpendicular planes of symmetry within the anisotropic body, and the material is, therefore, taken to be orthotropic in strength. Under this assumption, the coordinate system for the state of stress and the material symmetry must be the same. Thus the state of stress imposed on a body must be transformed to the coordinate system of material symmetry, and then the yield condition applied. For uniaxial ultimate strength, Tsai has suggested that the applicable equation for predicting strength variation as a function of direction to reinforcement is

$$\sigma_1' = \sigma_1 \Bigg/ \left[\cos^4\theta + \left\{\left(\frac{\sigma_1}{\tau}\right)^2 - 1\right\}\cos^2\theta\sin^2\theta + \left(\frac{\sigma_1}{\sigma_2}\right)^2\sin^4\theta\right] \tag{3. 14}$$

and for shear strength,

$$\tau_{max} = \sigma_1 \Bigg/ \left[\left(1 + \frac{\sigma_1}{\sigma_2} + \left(\frac{\sigma_1}{\sigma_2}\right)^2\right)\sin^2 2\theta + \left(\frac{\sigma_1}{\tau_o}\right)^2\cos^2\theta\right], \tag{3. 15}$$

where

σ_1 , σ_2 are ultimate uniaxial strengths in

X_1, X_2 directions

τ_o = interlaminar shear strength.

Before discussing the data and applying anisotropic elasticity theories, we should mention the following matters:

1) In this mechanical properties test screening program, the limitations of sample size had to be considered. This is of considerable significance in composite testing, where, in general, every new material requires careful examination of testing techniques

and particular attention to sample design. For this study, several extreme cases were considered:

a) relatively thin laminates

b) tubular braided samples.

Because shear strengths determined from quarter-point-loading flexure tests, core-shear, or Jacob bar-shear tests usually do not yield the same results, it was desirable to perform at least one series of similar tests on all the candidate materials, so that valid comparisons could be made. Since it is probable that shear failures inducedby compressive loads may differ appreciably from those induced by tensile loads, quarter-point-load flexure behavior is considerably influenced by beam span to depth ratios. On the other hand, simple core-shear tests, because they involve crushing of the reinforcement, may not be advisable, particularly when different reinforcing schemes are being studied. For these reasons, we decided to use both torsion and notched tensile-bar shear tests to measure shear properties wherever sample size permitted. Figures 84-86b illustrate typical samples used for the various types of composites.

3. Mechanical Tests and Results

An initial comparison of the candidate fabrics, as epoxy impregnated composites, was made by testing in tension in the plane of the fabric. Those initial tests were to ensure that proper composites had been made, resulting in a valid comparison of the interlaminar properties. The ordered results of these tests are shown in Table XIII. All of these tests were made on dog-bone-shaped tensile specimens whose thickness and resin content varied with the fabric employed in making the specimen. Several needled fabric specimens were molded to bring the resin content of the cured piece down to the value of the reference laminate. The needled structures were tried first, since it was felt that the distortion of the *Z* direction reinforcement from the compression during molding would be the least in this fabric.

A comparison, however, of the properties of the molded and cast samples in Tables XIII, XIV, and XV indicate that considerable movement of the Z direction fibers has taken place during molding. While there is considerable overlap in the data, the molded samples have a higher average tensile strength in the X (warp) direction and a lower average tensile strength in the Z direction than the cast samples. The molded samples also exhibit a higher average torsional shear strength around the **Z** axis, which also indicates that the Z direction fibers have been moved closer to the X, Y plane by the molding procedure. This reduction in the interlaminar properties decided us against requiring the composite to have a constant resin content, despite the additional problems in assessing the results.

TABLE XIII

COMPARISON OF X-DIRECTION (WARP) TENSILE PROPERTIES

Sample No.	Description	Ultimate Tensile Strength (psi)	Resin Content (percent)	Calculated Tensile Strength (psi)	Tensile Modulus (psi x 10^{-6})	Strain to Break (percent)
874-76	R[illegible] La[illegible]mi[illegible]	43,700	29.1	------	3.30	1.61
909-147	Matt No. 6 Molded	33,350	29.8	43,100	3.50	1.21
909-148	Matt No. 6 Molded	32,200	32.9	40,700	3.46	1.20
909-147	Av[illegible] 3-D Ep[illegible]xy	30,500	30.3	42,700	2.25	----
909-41	Avco 3-D Epoxy	30,100	28.3	44,300	1.94	----
910-9	Ha[illegible]n Fabric 1[illegible]yers	28,000	31.0	42,200	3.36	1.20
478-20-1	Do[illegible] Lo[illegible] Fabric laminate	22,200	28.8		2.72	1.42
909-103	Matt No. 3 Molded	21,350	34.0	39,900	2.65	1.14
909-146	Matt No. 6 Cast	18,200	51.1	28,300	2.13	1.02
909-56	Needled Matt and Fabric	18,050	60.6	23,000	1.53	1.54
909-85	Matt No. 2 Molded	17,300	20.9	50,850	3.55	1.04
	R[illegible]an Mu[illegible]li[illegible]w[illegible]	16,950	----	------	3.27	0.89
909-145	Matt No. 6 Cast	16,450	54.6	26,300	2.00	1.02
910-8	10-ply tufted back to back	14,200	49.0	29,600	2.00	----
909-68	Matt No. 1 Cast	12,600	70.2	18,200	1.38	1.11
909-59	Matt No. 1 Cast	11,650	69.3	18,600	1.28	1.02
909-75	10-ply tufted	8,740*	41.5	34,400	1.37	1.25
910-10A	Multiple Warp	7,220*	44.0	32,800	1.12	----
909-114	Needle St[illegible]le Fabric	6,950	77.9	13,900	0.80	1.00
	Ciba 6005 Resin	6,360	100.0	------	0.375	2.15
909-105	No-lock braid	3,580	28.7	44,000	1.22	0.34
909-106	No-lock braid	2,690	27.3	45,200	1.16	0.28

*Value low; sample was bow[illegible]d and c[illegible]acking [illegible]out when placed in grips

TABLE XIV

COMPARISON OF Z-DIRECTION TENSILE PROPERTIES

Sample No.	Description	Butt Tensile Strength psi
909-1	Avco 3-D Phenolic-Epoxy	41,700
19	Avco 3-D Epoxy	38,400
909-41	Avco 3-D Epoxy	38, 500
874-5 (26)	Avco 3-D Epoxy	38, 200
909-107	Avco 3-D Epoxy	35, 500
909-1 (48-1)	Avco 3-D Phenolic	33,000
478-201	Double Loop Fabric Laminate	4, 140
909-62	14 Ply Tufted	3,990
909-146	Matt No. 6 Cast	3,950
909-103	Matt No. 3 Molded	3, 610
909-56	Needled Matt and Fabric	3,540
909-81	Matt No. 2 Molded	3,440
909-68	Matt No. 1 Cast	3,430
909-114	Staple Needled Matt	3, 310
909-59	Matt No. 1 Cast	3, 240
909-147	Matt No. 6 Molded	3,080
910-10B	Multiwarp	2,720
909-145	Matt No. 6 Cast	2, 690
909-148	Matt No. 6 Molded	2,690
909-72	10-Ply Tufted not reimpregnated	2, 670
910-9	Hand-Sewn Cloth Laminate	2,660
874-76	Reference Laminate	2, 550
909-101	Matt No. 3 Molded	2, 540
909-75	10-Ply Tufted	1,770
910-8	10-Ply Tufted back to back	1, 190
909-105	Braid, no lock	885
909-85	Matt No, 3 Molded	848
909-83	Matt No. 2 Molded	618
909-106	Braid, no lock	337

TABLE XV

COMPARISON OF TORSIONAL SHEAR PROPERTIES

Sample No.	Description	'orsiona Strength (psi)	Sample No.	Description	Torsional Modulus (psi x 10^{-6})
19	Avco 3-D	12,300	478-20-1	Double Loop Fabric Laminate	0.543
909-41	Avco 3-D	12,200	19	Avco 3-D	0.535
909-107	Avco 3-D	12,150		Raypan Multiwarp	0. 502
478-20-	Double Loop Fabric Laminat	7,430	909-107	Avco 3-D	0.435
909-56	Needled Matt	6,400	909-106	No-lock braid	0.430
	Raypan Multiwarp	6, 130	901-41	Avco 3-D	0.410
909-59	Matt No. 1 Cast	6, 010	909-147	Matt No. 6 Molded	0. 370
909-68	Matt No. Cast	5,920	909-148	Matt No. 6 Molded	0.360
909-101	Matt No. 3 Molded	5,770	909-101	Matt No. 3 Molded	0. 340
909-148	Matt No. 6 Molded	5,650	874-76	Reference Laminates	0. 330
909-147	Matt No. 6 Molded	5,610	909-146	Matt No. 6 Molded	0. 270
909-114	Staple Needled Matt	5,400	909-85	Matt No. 2 Molded	0. 270
909-62	14-Ply Tufted	5,570	909-56	Needled Matt	0.245
910-10B	Multiwarp	5,350	910-9	Hand-Sewn Cloth Laminate	0. 240
910-10A	Knitted Multiwarp	5, 090	909-145	Matt No. 6 Cast	0.230
909-145	Matt No, 6 Cast	4,940	909-83	Matt No. 2 Molded	0. 230
909-146	Matt No. 6 Cast	4,940	910-10B	Multiwarp	0.210
909-75	10-Ply Tufted	4, 840	909-59	Matt No. 1 Cast	0.210
909-106	No-lock braid	3,700	910-10	Knitted Multiwarp	0.200
874-76	Reference Laminates	3,200	909-62	14-Ply Tufted	0.200
910-8	10-Ply Tufted back to back	3,190	909-68	Matt No. 1 Cast	0. 190
909-85	Matt No. 2 Molded	3,060	909-75	10-Ply Tufted	0.180
909-83	Matt No. 2 Molded	2, 870	909-105	\lo-lock braid	0. 180
910-9	Hand-Sewn Cloth Laminate	2, 140	909-114	Stapled Needled Matt	0. 170
909-105	No-lock braid	a95	910-8	10-Ply Tufted back to back	0. 160

The reference laminate had the highest tensile strength in the X, Y plane, as expected, since all of the reinforcement is in that plane. All of the candidate composites should be lower in strength in the X (warp) direction, because some of the reinforcement is in the Z direction and the X, Y direction reinforcement ratio has not been changed. The column labeled "Calculated Tensile Strength" is derived from a ratioing of the composite resin and reinforcement volume percent to that of reference laminate, assuming all reinforcement is in the X, Y plane with the X, Y distribution the same as that in the reference laminate. The equation employed is given below:

(volume, percent glass) (strength of glass) + (volume, percent resin) (strength of resin) = calculated strength of composite.

The values have been normalized by back calculating the strength of the glass from the data for the reference laminate. The actual values for ultimate tensile strength range from about 6 to about 80 percent of the calculated values, but, if the percentage of glass in the Z direction (known for Avco 3-D) is subtracted from the total reinforcement content for the Avco 3-D specimens, and the strength is recalculated for the lower glass content, the actual value is 8-percent higher than the calculated value. This is within experimental error. The vendor-made candidate fabrics that had unknown percentages of reinforcement in the Z direction, though less than the Avco 3-D sample, generally have a lower fraction of the calculated strength than the Avco fabrics. One cause of this lower strength is the looseness of the fabric weave. The resin contracts during cure, and, if the reinforcement is not closely enough packed, cracks are formed. These cracks were particularly evident around the free loops of the tufted samples. The failures initiate at these cracks, thus giving low values. Care was taken to eliminate gross cracks from the samples, but fine hairline cracks were impossible to see and, therefore, impossible to eliminate, though they would probably have just as disastrous an effect on strength. The extremely low values for the braided samples stem also from the direction of testing, as described in the preceeding analytical section, since the samples were oriented axially, and the braided yarns were wound at about a 45-degree angle with the axis as shown in Figure 20. This, however, only accounts for a factor of two; so all of the causes are not known.

The interlaminar strength data, butt tensile in Table XIV and torsional shear properties in Table XV are very interesting despite the problems concerned in comparing unequals. The butt tensile strength values show the largest range, from 337 psi for braid up to 41, 700 psi for an Avco 3-D sample, while the reference laminate shows a 2, 550 psi strength. Both sample shape and direction of reinforcement are critical parameters affecting the interlaminar strength data. The first, sample size and shape, determines whether the maximum stress occurs in the center of the sample, the end regions, or in the adhesive of the bond line. The grip material (aluminum) to which the specimens are bonded has a different modulus and Poisson's ratio than the candidate composites. This creates shear stresses in the bond line and the end regions of the sample so that, if failure occurs here, a low value for the tensile strength is recorded. The 1-inch-diameter disks tested as butt tensile specimens varied in thickness from slightly less than 1/4 to greater than 1 inch. The Avco 3-D fabrics were of such size that regular dogbone shapes could be obtained in the Z direction, and the double-loop fabric laminates were only slightly reduced in length. The more secure grip obtained on these specimens and elimination of shear stresses on the sample end may account for some of the superiority **shown** but the larger percentage of reinforcement in the Z direction is the main factor for the Avco 3-D. The only other sample in which percentage of *Z* direction reinforcement approaches the Avco 3-D is the multiple-warp sample 910-10B, and the woven density of this fabric is much lower (1. 00 multiwarp versus 1. 38 Avco 3-D), and the multiwarp is much thinner (only 1/4-inch thickness). In spite of all these deterrents and the fact that most of the data, except Avco 3-D and reference laminate, tend to err on the low side, 9 out of 13 candidate materials had higher Z direction tensile strength than the reference. The two candidate materials that were significantly lower than the reference were the 10-ply tufted, where very thin samples (slightly less than 1/4-inch) were tested, and the no-lock braid (3/4-inch thick). Although the differences are not large, the data presented are corroborated by the shear data and the thermal shock data. The main points in the data are that *any* reinforcement in the *Z* direction shows an improvement over a normal laminate, while a fabric of equivalent density with large amounts ($\approx$ 35 percent) of Z direction reinforcement can show a 13 to 16 times increase in strength.

The torsional shear strength values of the vendor-supplied candidate materials (Table XV) exhibit a larger range than the tensile strength data. The multiple-warp samples show better relative strength in shear than in tension, and the molded needled fabric (909-147 and 909-148) has higher values than the cast samples (909-145 and 909-146).

In general, the same conclusions can be made for the torsional shear data as for the tensile data; i. e. , even small amounts of reinforcement in the interlaminar direction improve the shear strength, and high fabric density with high percentage Z direction threads give very large improvements (4X for Avco 3-D).

4. Thermal Shock Test and Results

Since interlaminar mechanical properties have not been experimentally correlated with thermal shock resistance, the candidate materials, as composites, were subjected to three thermal shock tests. These tests were a low-radiant-heating flux test, conducted in a metallurgical furnace at 2100" F, and a two high-flux tests, in which quartz lamps with 4000°F elements were employed as the energy source. The flux rate at the samples when placed 1 inch from the bank of quartz lamps, operating with a 4000" F element temperature, is 27 Btu/ft^2-sec, as compared to a nominal value of 150 Btu/ft^2-sec for a rocket exhaust. Not all of the sections of the ablative material surrounding the metallic throat insert will be subjected to the maximum heat flux, so that the quartz-lamp high-flux thermal-shock tests will be a fair approximation of the actual thruster environment. It does, however, produce severe and extensive cracking in the phenolic and epoxy reference material with 15 seconds exposure, so it appears that the major phenomenological features of actual firing are simulated.

The thermal shock tests that were performed show specifically that reinforcement is required in the Z direction to prevent the extensive and severe cracking exhibited by the control composites. The extent of this reinforcement necessary to withstand the stresses generated by the thermal shock depends, as expected, upon the severity of the heating level. The materials with the highest Z direction reinforcement show the best shock resistance as well as the highest interlaminar shear strength, These materials are the Avco **3-D** multiple loop fabric laminates and the multiple-ply tufted materials. Cast-needled samples, however, appear very promising. Further development of the quartz-lamp shock test, to give more quantitative results, could result in a very useful diagnostic tool and quality control test.

Due to failure of the power supply and heating elements of the electrical apparatus for the thermal shock test, alternative methods were employed.

a. Low Flux Furnace Thermal Shock Test

An electrically heated metallurgical furnace was used as the heat source for a low-flux density test, and a bank of 18 quartz lamps as the high-flux test. The furnace consists of a 3 1/2-inch-diameter pipe heated by four globar units in a square array parallel to the axis of the tube. The array is surrounded by fire brick over half of the tube length, while the other end is water cooled through copper coils brazed to the tube. The furnace temperature was set at 2100" F, and an argon atmosphere was maintained by bleeding the gas through the tube. A sample piece of glass reinforced phenolic (Figures 90 and 91) was instrumented with a thermocouple on the surface and in the center, revealing that the surface temperature reached a maximum of ≈ 1525" F within 15–20 seconds. The sample showed severe and extensive cracking within 1 minute. The samples tested were machined into a 1-inch diameter disks, whose thickness varied with the fabric thickness. Control materials were glass cloth laminates, with epoxy resin for one, and phenolic resin for the other. All the candidate materials were impregnated with epoxy resin.

The heat flux in the furnace is considerably less than the original heater, since the furnace temperature is about 2100" F while the heater surface temperature expected from the tungsten elements was about 3000° F.

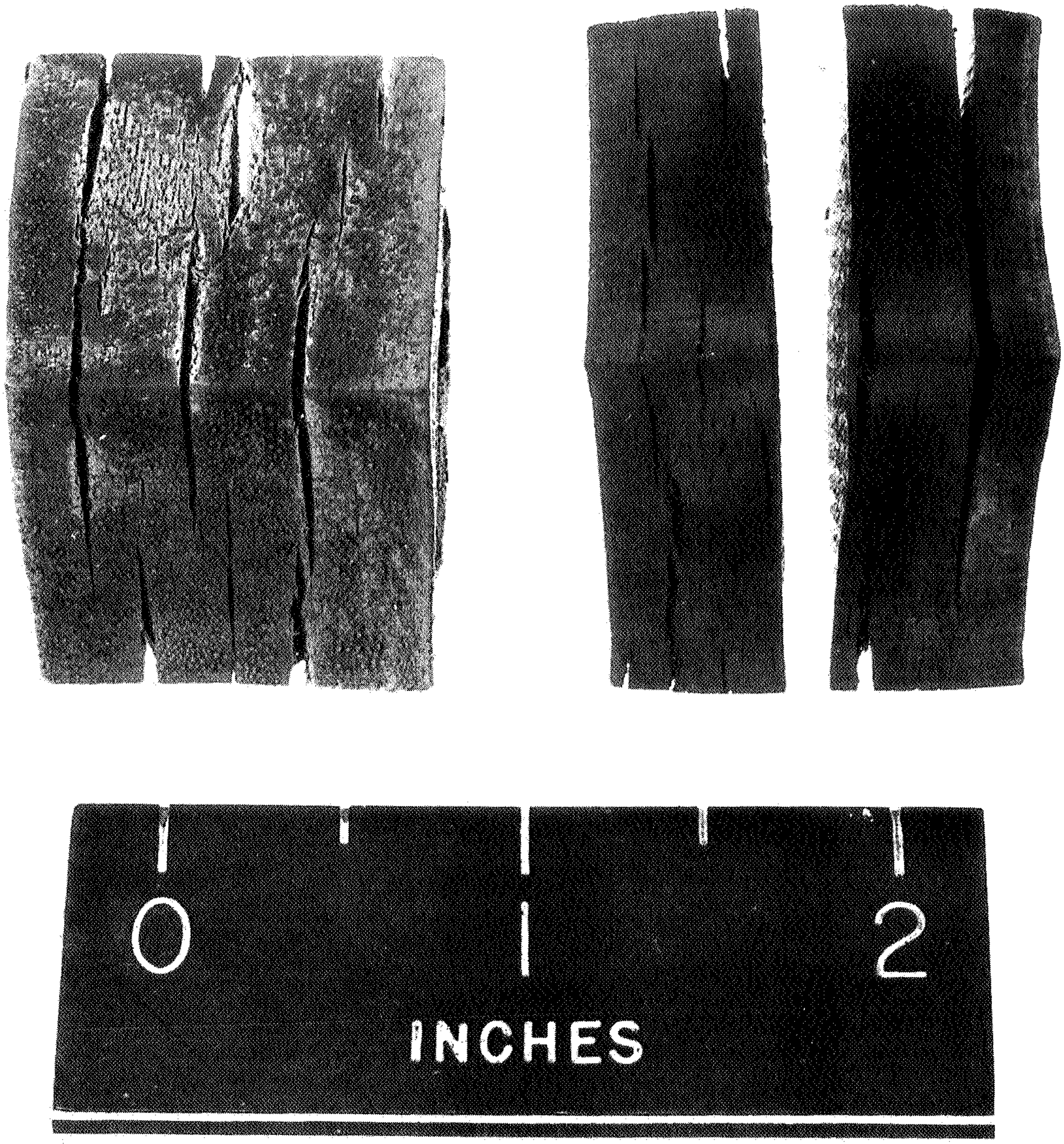

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Figure 90 LEFT: PHENOLIC-GLASS REFERENCE MATERIAL, 20-MINUTE EXPOSURE. RIGHT: 2-MINUTE EXPOSURE

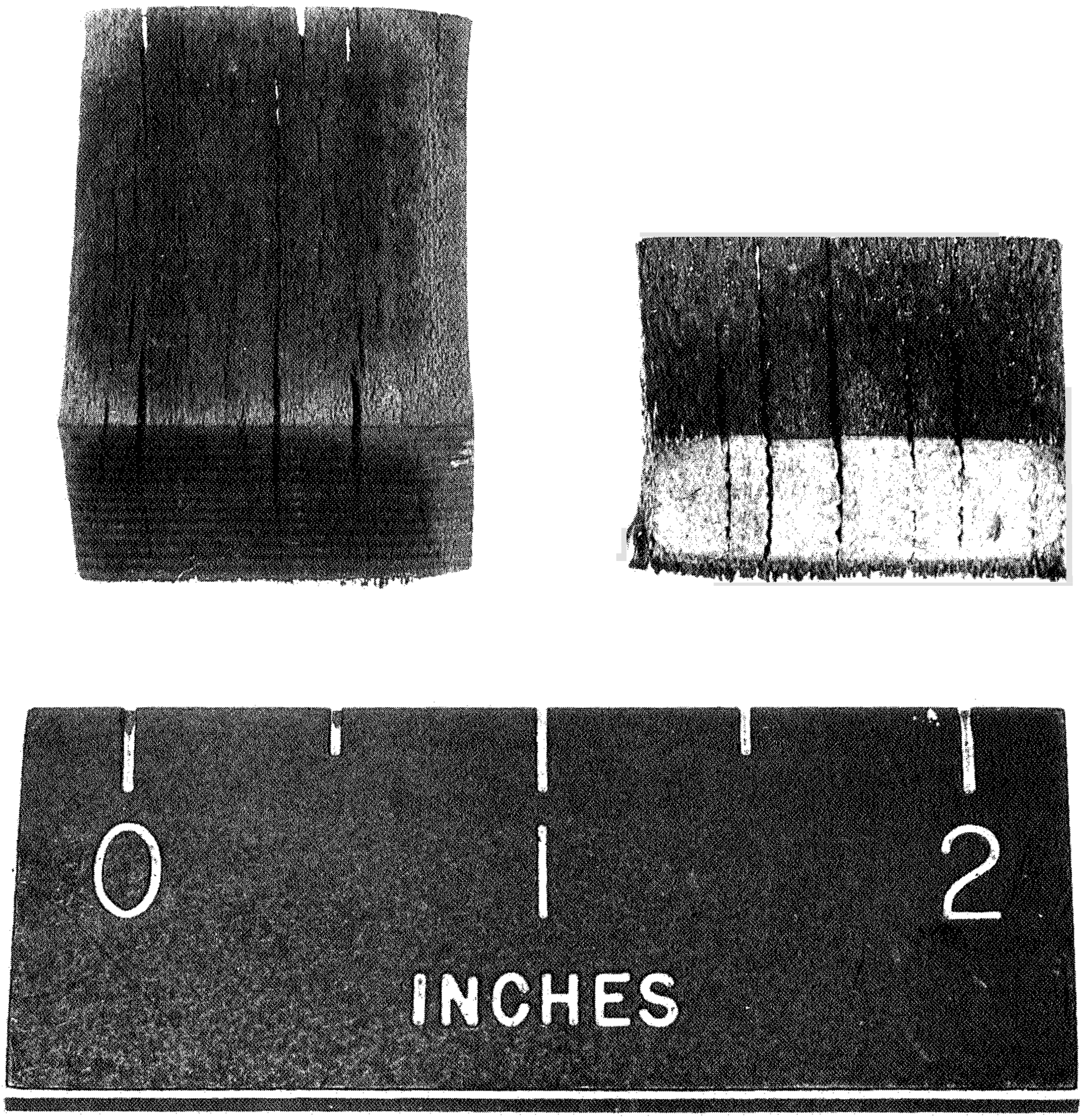

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Figure 91 LEFT: GLASS-PHENOLIC REFERENCE MATERIAL. RIGHT: GLASS-EPOXY. (1-MINUTE EXPOSURE)

Control laminates of glass-phenolic and glass-epoxy, however, showed severe and extensive cracks after 1-minute exposure in the furnace. (See Figure 91.) Thus the thermal shock, though lower than expected from the tungsten element was high enough to cause cracking in the control materials.

Figures 91—100 show the char pattern and cracking that occurred in 21 different samples and a pure epoxy resin control. Table XVI gives a qualitative ordering of the samples by thermal shock resistance, using extent and concentration of cracks as the criteria. An interesting aspect of this ordering is that six of the samples most susceptible to crack formation and severity of cracks formed are all molded needled materials. The only exception is the non-locked braid sample. These fabrics, needled to various extents, were molded to stops so that higher reinforcement content could be obtained in the composite. This compression in the interlaminar direction apparently disturbed the fiber orientation in the Z direction, as the cast needled fabrics appeared to resist the thermal shock much better, even though the fiber contents in the molded samples are higher. Note particularly the comparison of 909-145 and 146 (cast) with 909-147 and 148 (molded), since all four samples were from the most heavily needled sample from J. P. Stevens. 909-56, 59, and 68 were also cast samples and looked better than any of the molded samples. Comparison of 99-147 and 148 with 909-101 and 103 as well as comparison of 909-145 and 146 with 909-59 and 68 indicates that needling density may also effect the thermal shock resistance, though to a lesser extent than does the fact that the sample was molded or cast, Matt No. 6, 909-145-148, was needled 3 1/2 times as much as Matt No. 1, 909-59 and 68, and 4 1/2 times as much as Matt No. 3, 909-101 and 103, (See Table III.) All but one of these samples that had at least as much reinforcement as the heavily needled Matt No. 6 showed no cracking. The single exception was 910-8, a 10-ply tufted sample, impregnated back to back, in which the unreinforced interface shows slight cracking,

The samples that showed no cracking included tufted, Avco 3-D, and multiple-warp fabrics.

b. High-Flux Quartz Heating Lamp

To determine whether this low level of reinforcement was inherently all that was necessary for resistance to thermal shock, samples were also subjected to the much higher radiant flux level and hotter source temperature of a bank of quartz lamps, The filament temperature of the eighteen 1000 watt lamps in the array was held at 4000" F, a close approximation of the temperature in the thruster exhaust. With the samples stationed 1 inch from the array, the flux level from the quartz lamps was 27 Btu/ft^2-sec, and is estimated to be about 15—20 times that from the furnace at a 1-1/2- to 2-inch distance. The results shown in Figures 101—104 and listed in Table XVII do show a different break point

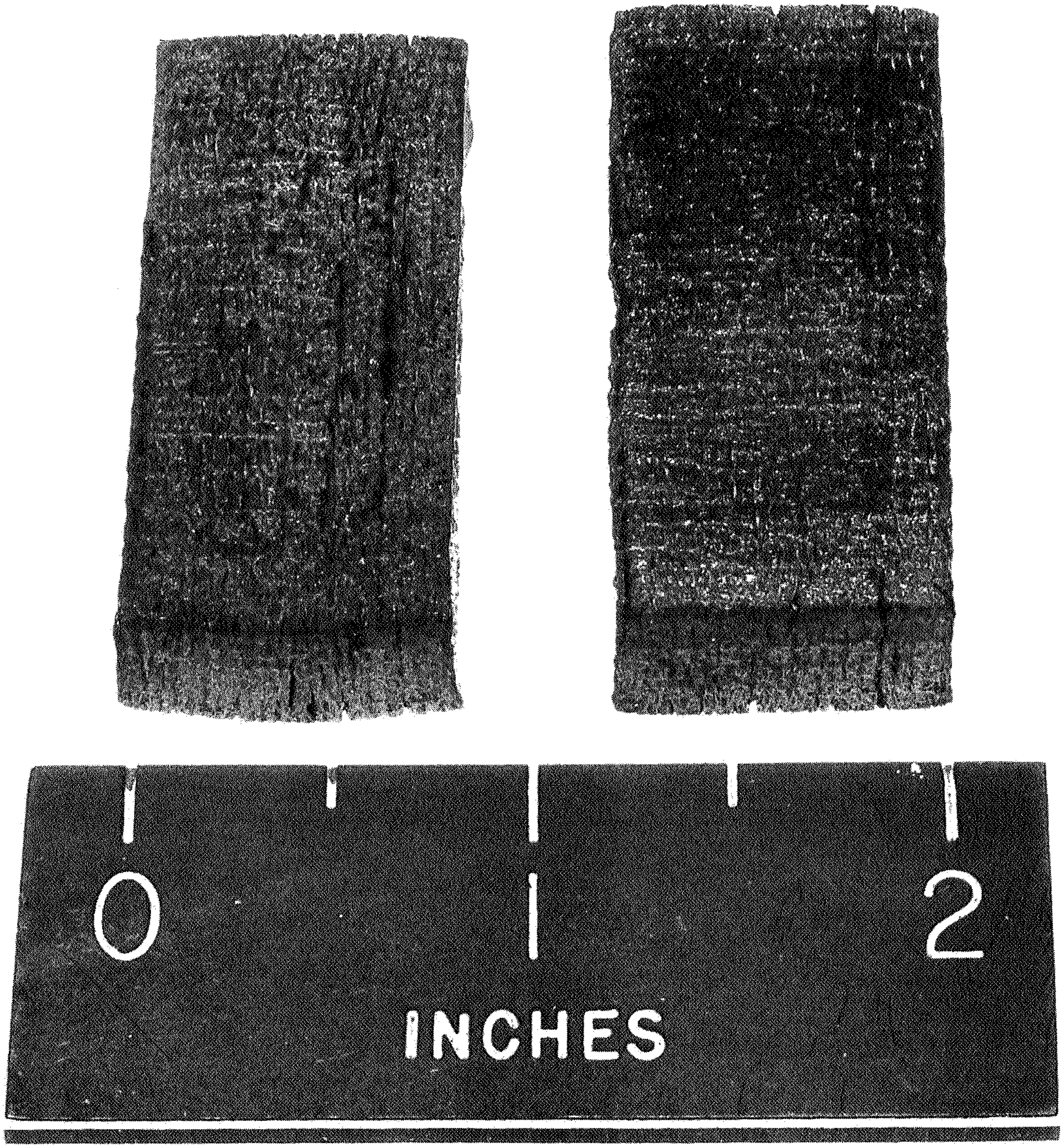

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Figure 92 LEFT: NEEDLED MATT (909-56), 2-MINUTE EXPOSURE. RIGHT: 1-MINUTE EXPOSURE

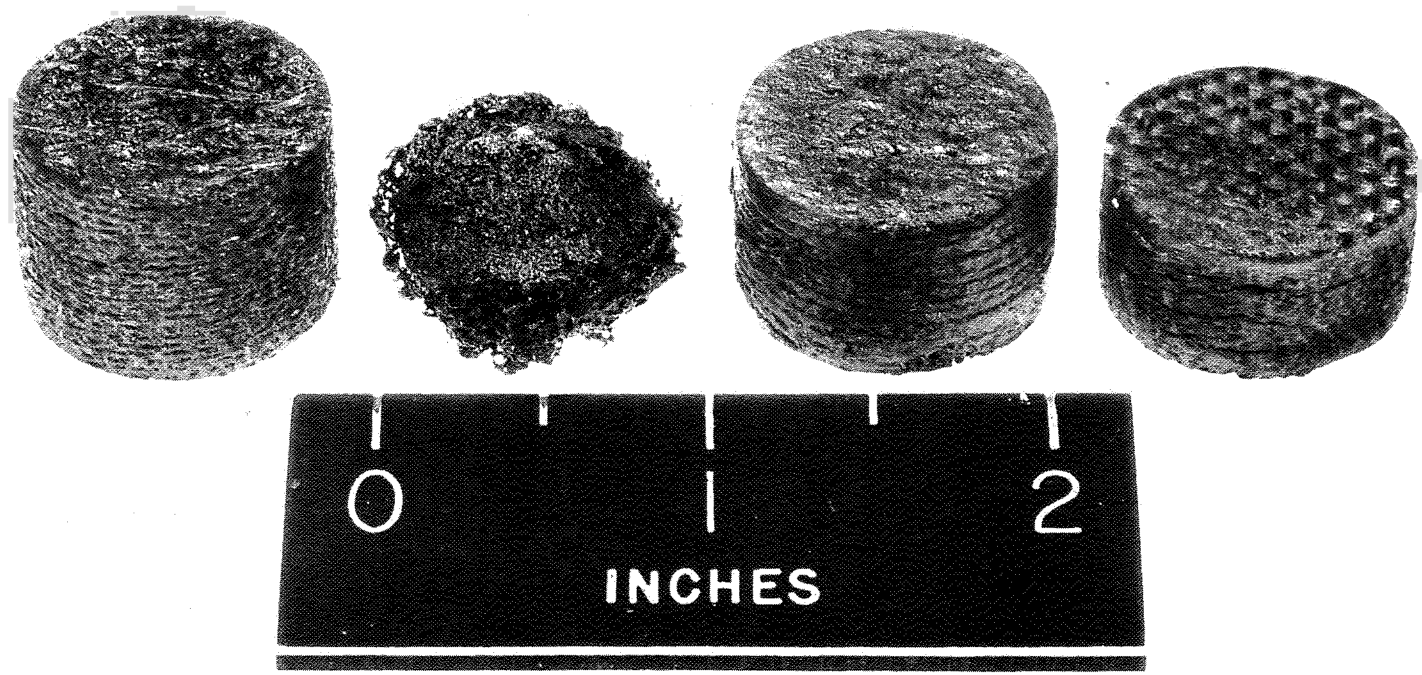

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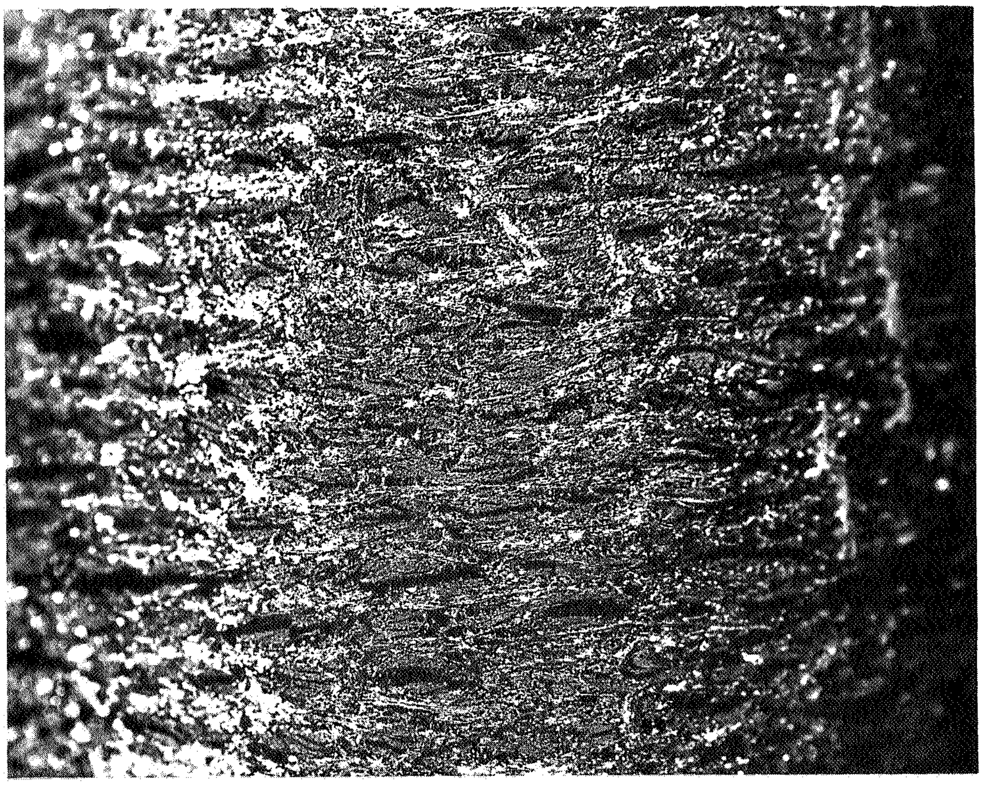
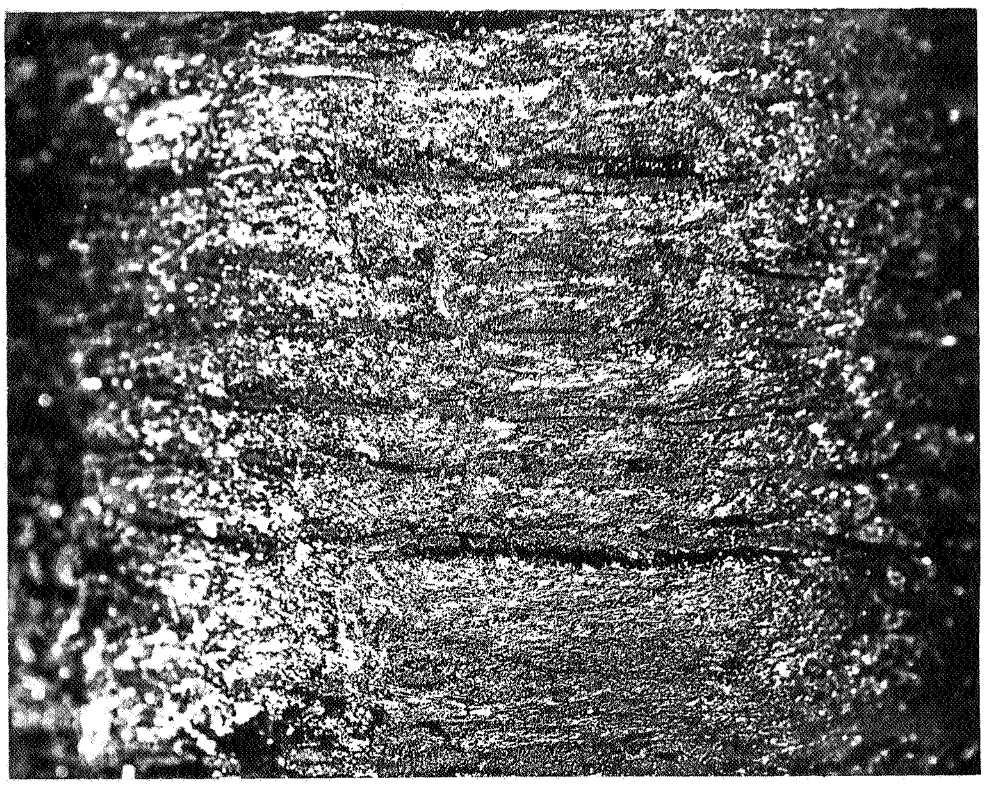
Figure 93 LEFT TO RIGHT (1-MINUTE EXPOSURE): NEEDLED MATT (909-56); PURE EPOXY RESIN: NEEDLED FABRIC NO. 1, CAST (909-59); NEEDLED FABRIC NO. 6, MOLDED (909-147)



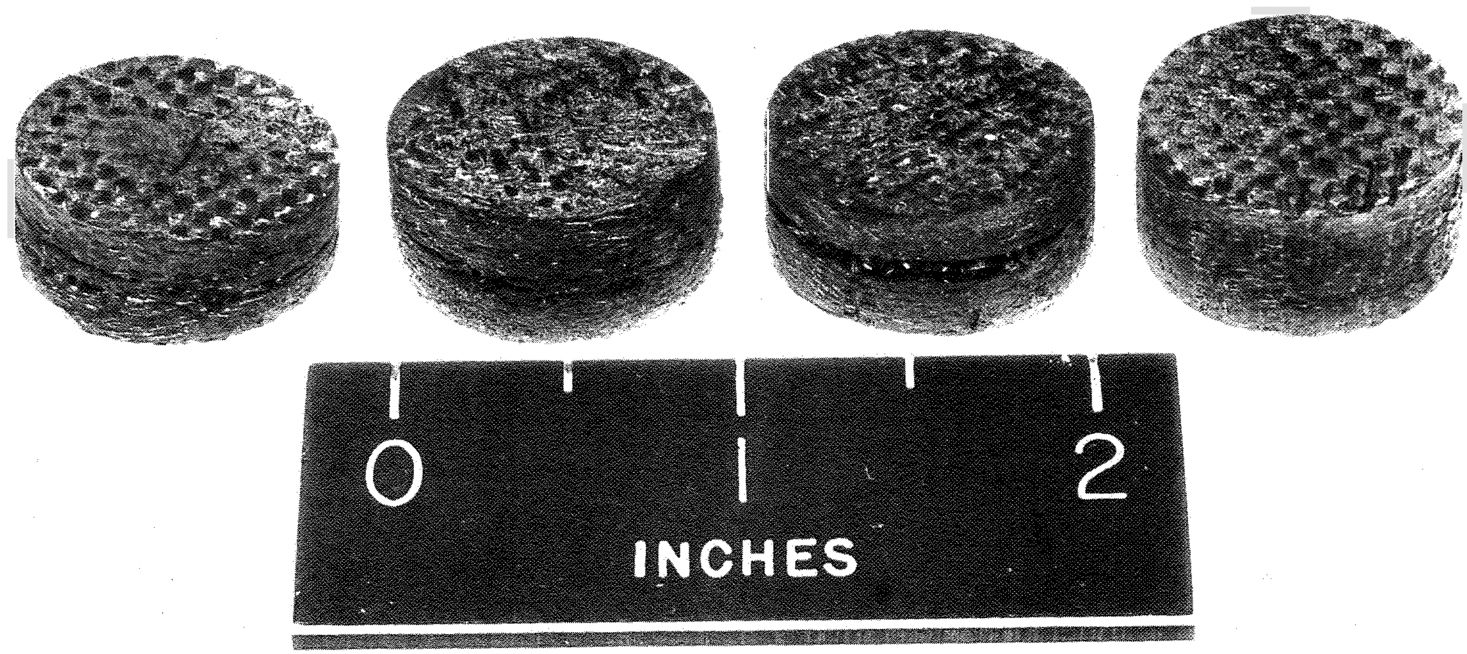
8 X MAGNIFICATION 909-56 NEEDLED MATT



8 X MAGNIFICATION 909-59 NEEDLED FABRIC NO. I **CAST**

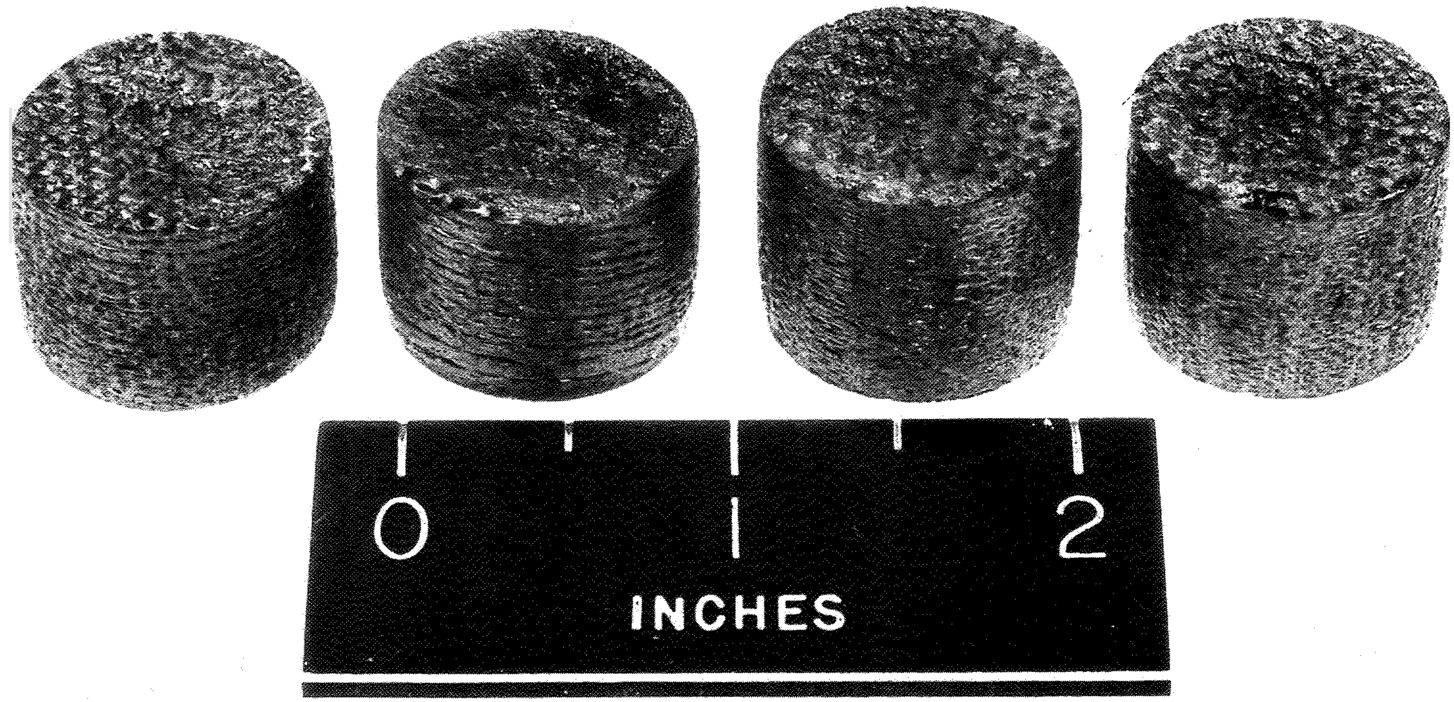
86-2140

Figure 94 TOP: NEEDLED MATT (909-56). BOTTOM NEEDLED FABRIC NO. 1, CAST (909-59). (8X MAGNIFICATION)



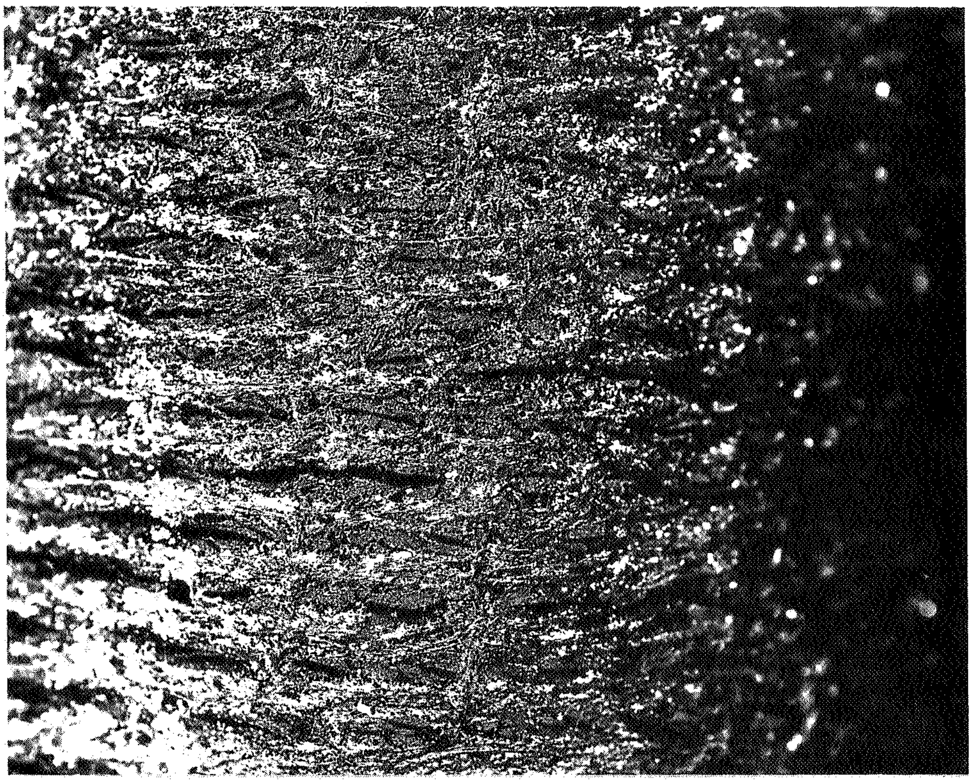
160863

Figure 95 LEFT TO RIGHT (1-MINUTE EXPOSURE): NEEDLED FABRIC NO.2, MOLDED (909-83); NEEDLED FABRIC NO. 3, MOLDED (909-103); NEEDLED FABRIC NO 3, MOLDED (909-101; NEEDLED FABRIC NO.6, MOLDED (909-148)

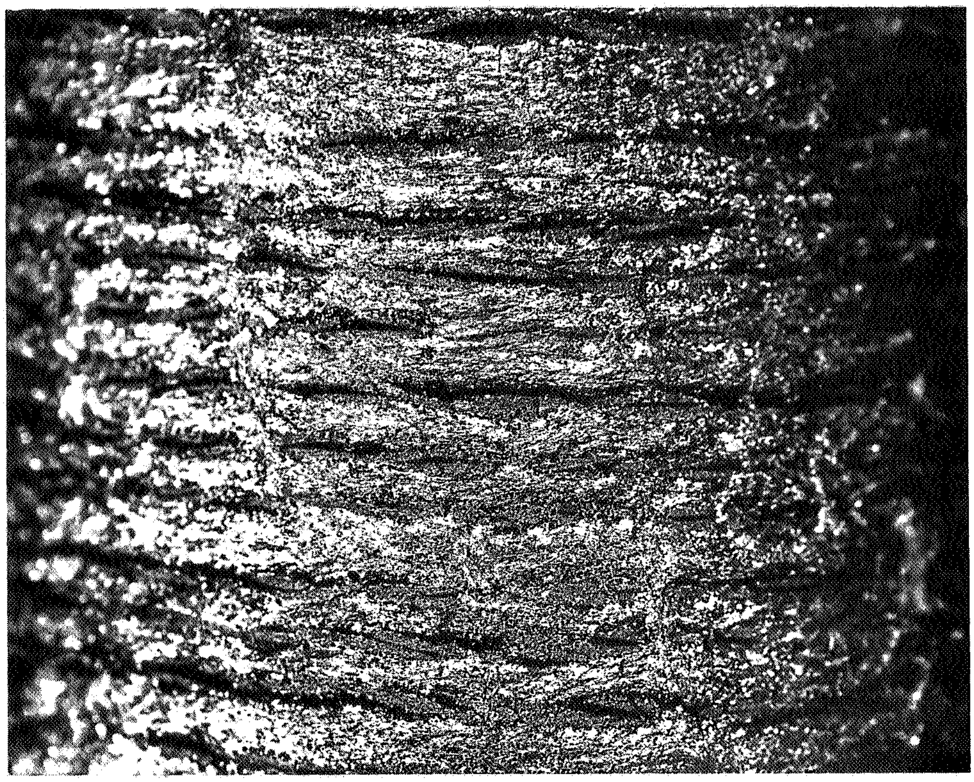


16066A

Figure 96 LEFT TO RIGHT (1-MINUTE EXPOSURE): NEEDLED MATT (909-56); NEEDLED MATT NO.1, CAST (909-6); NEEDLED FABRIC NO.6, CAST (909-145); NEEDLED FABRIC NO.6, CAST (909-146)



8X MAGNIFICATION 909-56 NEEDLED MATT



8X MAGNIFICATION 909-68 NEEDLED FABRIC NO.I CAST

86-2141

Figure 97 TOP: NEEDLED MATT (909-56). BOTTOM: NEEDLED FABRIC NO.I, CAST (909-63). (8X MAGNIFICATION)

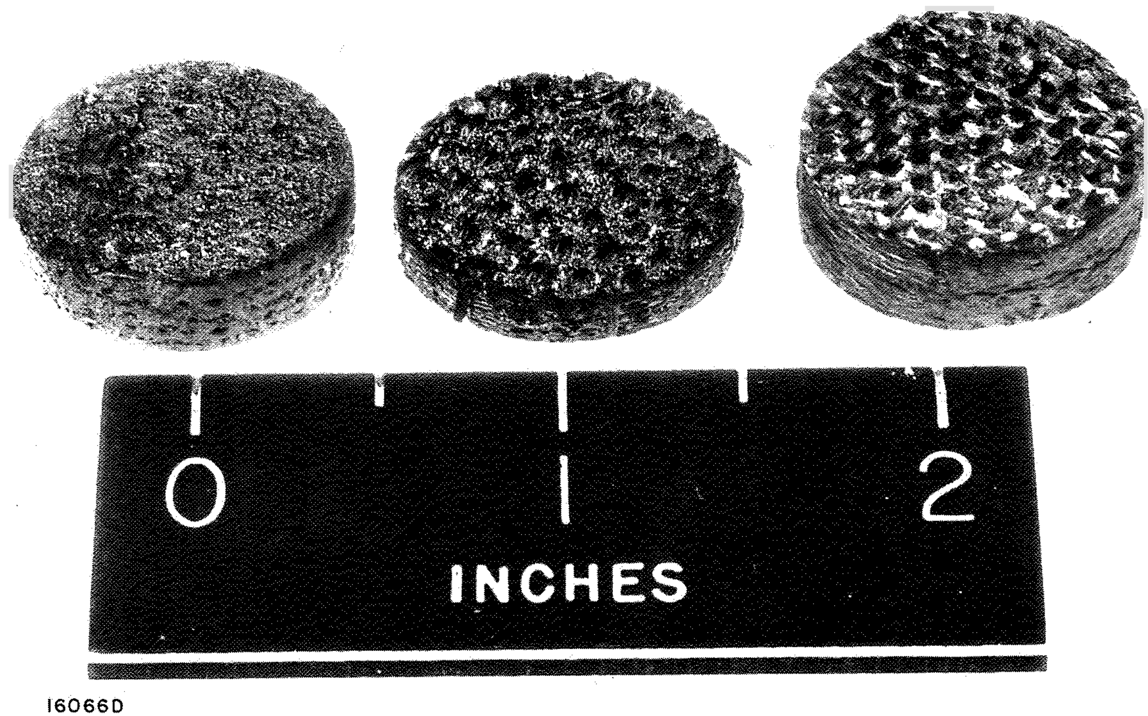
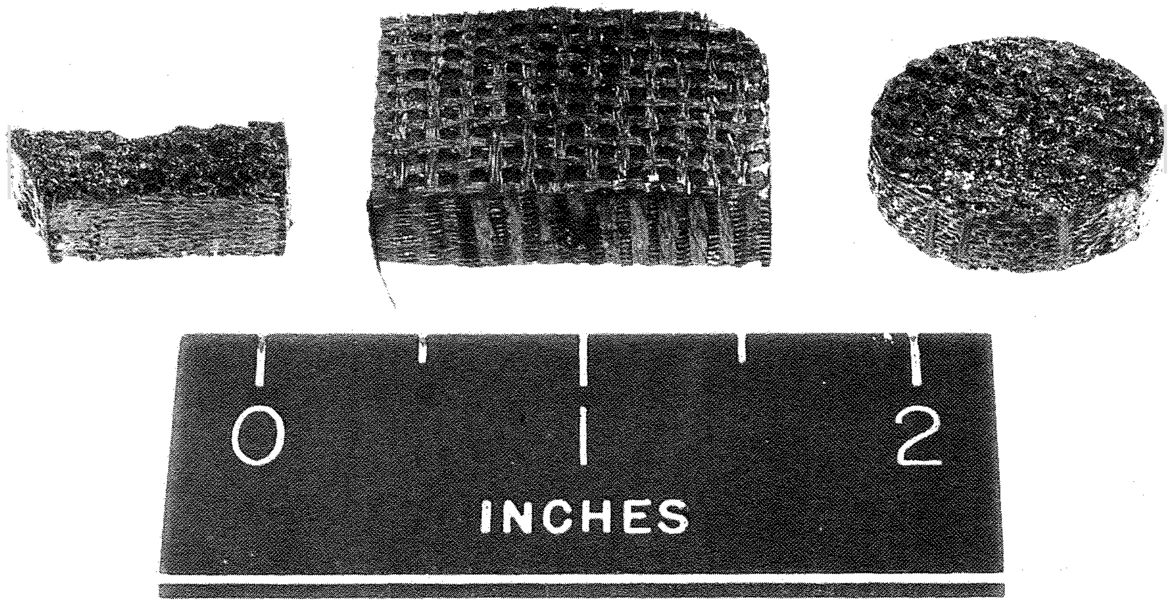
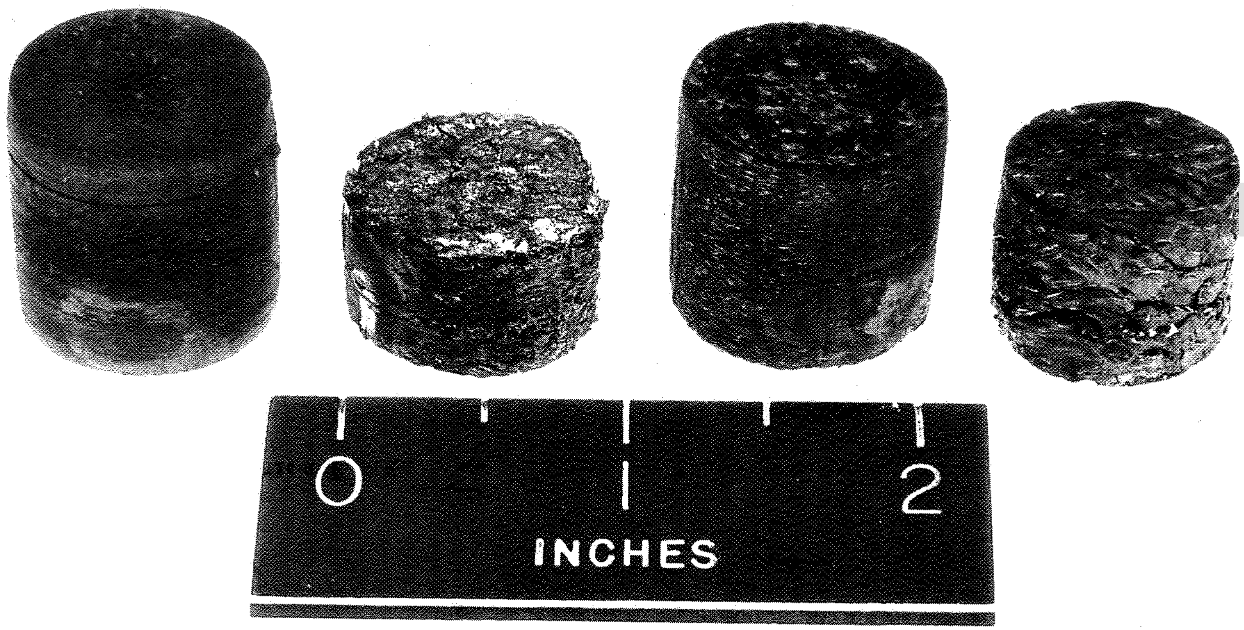


Figure 98 LEFT TO RIGHT: NEEDLED FABRIC NO. 1, CAST (909-49); RE-IMPREGNATED TUFTED FABRIC, 10-PLY (909-72); NEEDLED FABRIC NO. 2, MOLDED (909-85)



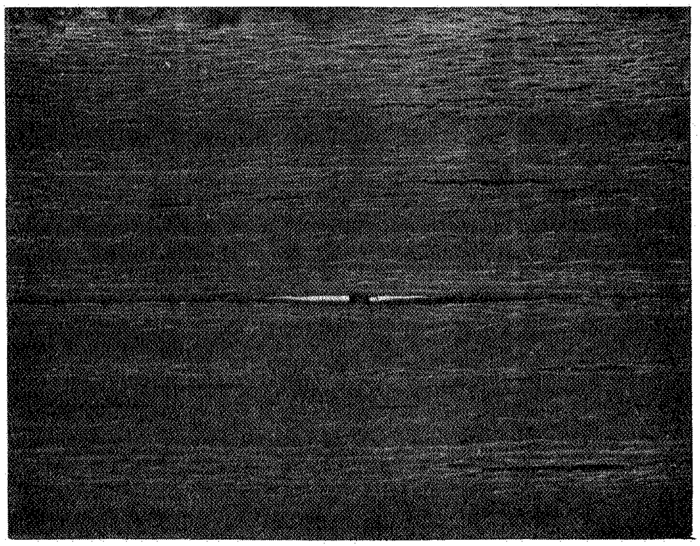
16068A

Figure 99 LEFT TO RIGHT (1-MINUTE EXPOSURE): NOT RE-IMPREGNATED TUFTED FABRIC, 14-PLY (909-62); AVCO 3-D (909-41); RE-IMPREGNATED TUFTED FABRIC, 14-PLY (909-62)

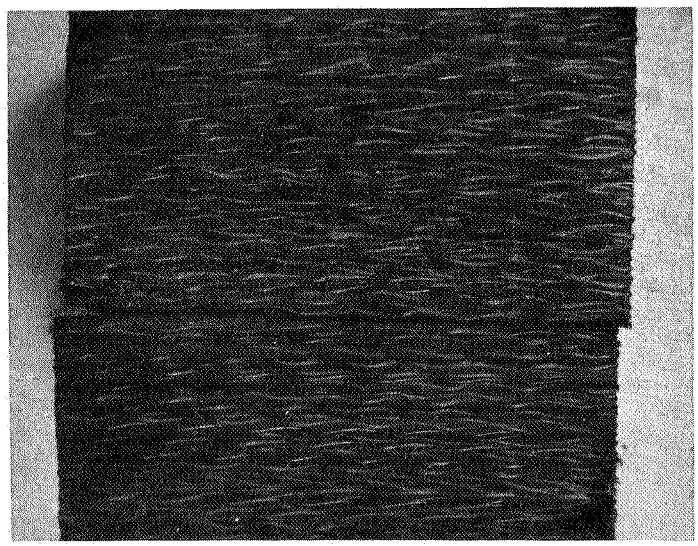


16068B

Figure 100 LEFT TO RIGHT (1-MINUTE EXPOSURE): PHENOLIC-GLASS REFERENCE LAMINATE; TUFTED FABRIC, 10-PLY, CAST BACK-TO-BACK (910-8); HAND-SEWN LAYERS OF FABRIC (910-9); NON-LOCKED BRAID (909-105)



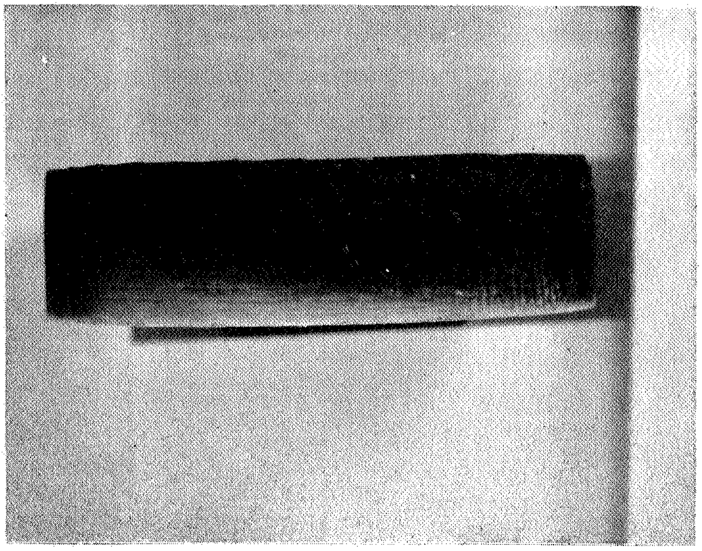
15 SECOND EXPOSURE PHENOLIC-GLASS REFERENCE LAMINATE



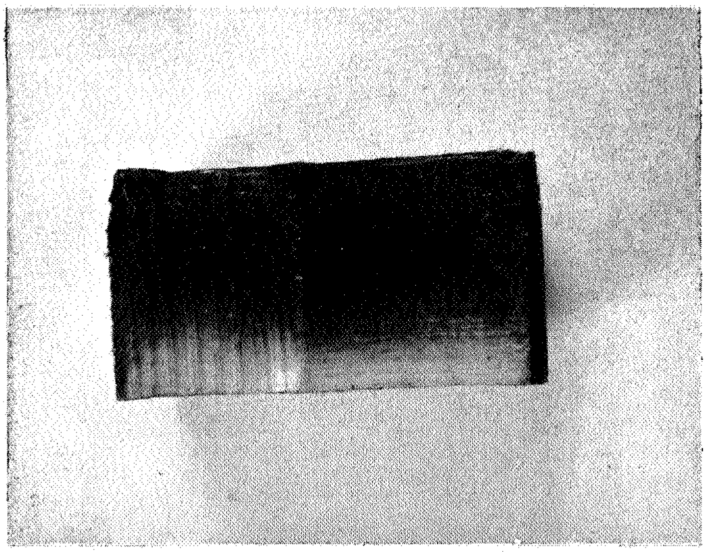
15 SECOND EXPOSURE EPOXY-GLASS REFERENCE LAMINATE

86-2142

Figure 101 TOP: PHENOLIC-GLASS REFERENCE. BOTTOM EPOXY-GLASS REFERENCE. (15-SECOND EXPOSURE)



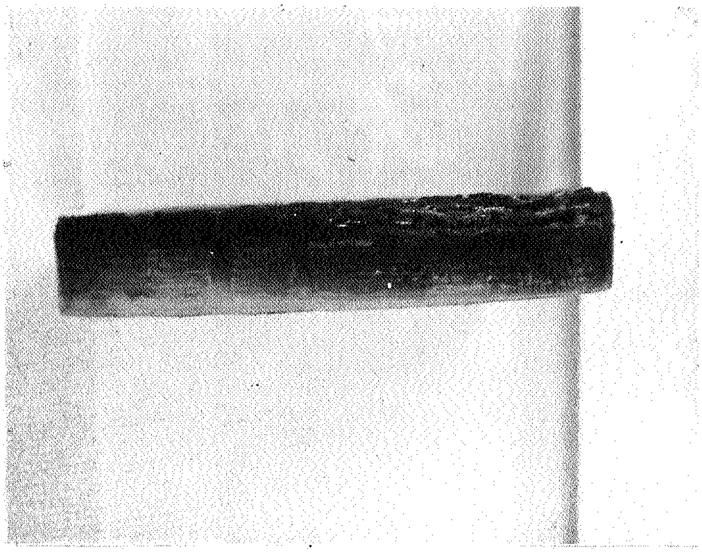
15 SECOND EXPOSURE 909-83 NEEDLED FABRIC
NO.2 MOLDED



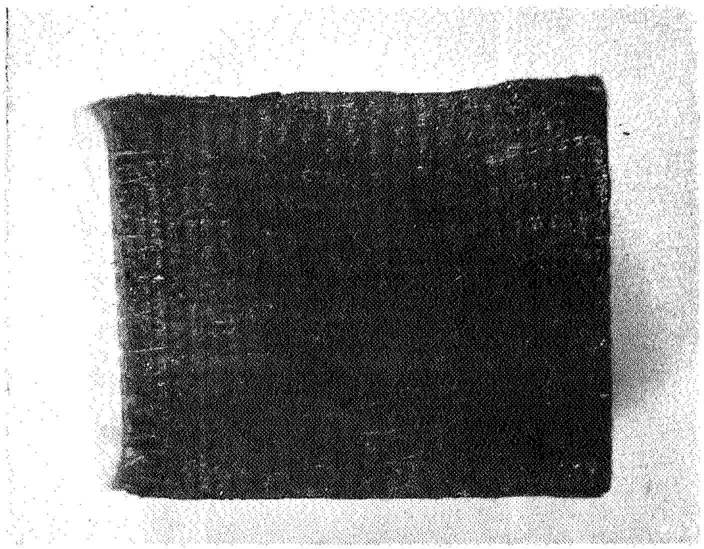
15 SECOND EXPOSURE 909-103 NEEDLED FABRIC
NO. 3 MOLDED

86-2143

Figure 102 TOP: NEEDLED FABRIC NO. 2, MOLDED (909-83); BOTTOM NEEDLED FABRIC NO. 3, MOLDED (909-103). (15-SECOND EXPOSURE)



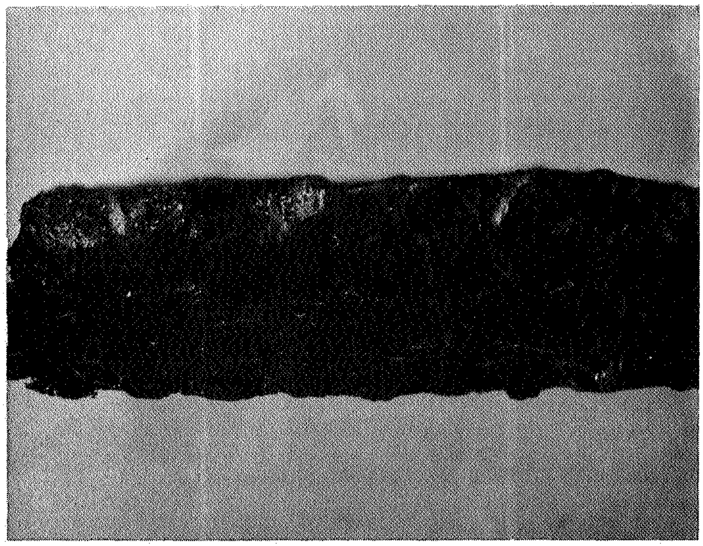
I5 SECOND EXPOSURE 909-75 IO PLY TUFTED
NOT REIMPREGNATED



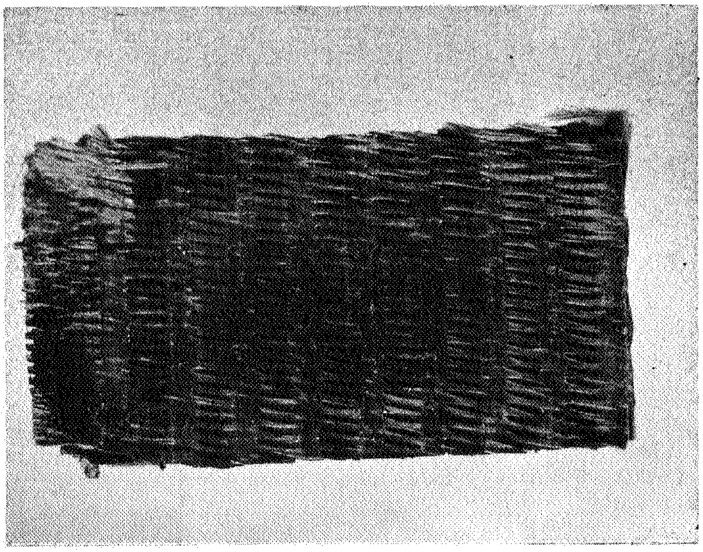
I5 SECOND EXPOSURE 909-59 NEEDLED FABRIC
NO. I CAST

86-2144

Figure 103 TOP: TUFTED, 10-PLY, NOT RE-IMPREGNATED *(909-75).* BOTTOM NEEDLED FABRIC NO. 2, CAST *(909-59).* (15-SECOND EXPOSURE)



15 SECOND EXPOSURE 909-72 10 PLY TUFTED
NOT IMPREGNATED



15 SECOND EXPOSURE AVCO 3-D

86-2145

Figure 104 TOP: TUFTED, 10-PLY, NOT RE-IMPREGNATED (909-72). BOTTOM AVCO 3-D (904-41). (15-SECOND EXPOSURE)

TABLE XVI

THERMAL SHOCK TEST: LOW FLUX RATE
1 MINUTE RESIDENCE TIME IN 2100°F OVEN

Sample Number	Sample Description*	Z-Direction Reinforcemen Density (per in^2)	Damage Description
874-76	Epoxy reference phenolic reference	none none	extensive and severe cracks
909-105	non-locked braid	none	extensive and severe cracks
909-101	needled fabric No. 3 molded	320 penetrations	severe cracks
909-103	needled fabric No. 3 molded	320 penetrations	severe cracks
909-83	needled fabric No. 2 molded	400 penetrations	severe cracks
909-147	needled fabric No. 6 molded	1400 penetrations	severe cracks
909-85	needled fabric No. 2 molded	400 penetrations	severe cracks
909-148	needled fabric No. 6 molded	1400 penetrations	severe cracks
910-9	hand sewn layers of cloth	9-16 threads	severe cracks
909-59	needled fabric No. 1 cast	400 penetrations	very slight cracks and visible pores
909-68	needled fabric No. 1 cast	400 penetrations	very slight cracks andvisible pores
910-8	10 ply tufted fabric back to back	64 tufts	visible pores
909-56	needledmatt andfabri	unknown	visible pores
909-56	needled matt and fabri	unknown	visible pores
909-145	needled fabric No. 6 cast	1400 penetrations	no cracks
909-146	needled fabric No. 6 cast	1400 penetrations	no cracks
909-49	needled fabric No. 1	400 penetrations	no cracks
909-72	10-ply tufted fabric reimpregnated	64 tufts	no cracks
909-62	14-ply tufted fabric not reimpregnated	64 tufts	no cracks
909-41	Avco 3-D	2400 yarns	no cracks

*More detailed sample descriptions in Tables V, VI, and VII

TABLE XVII

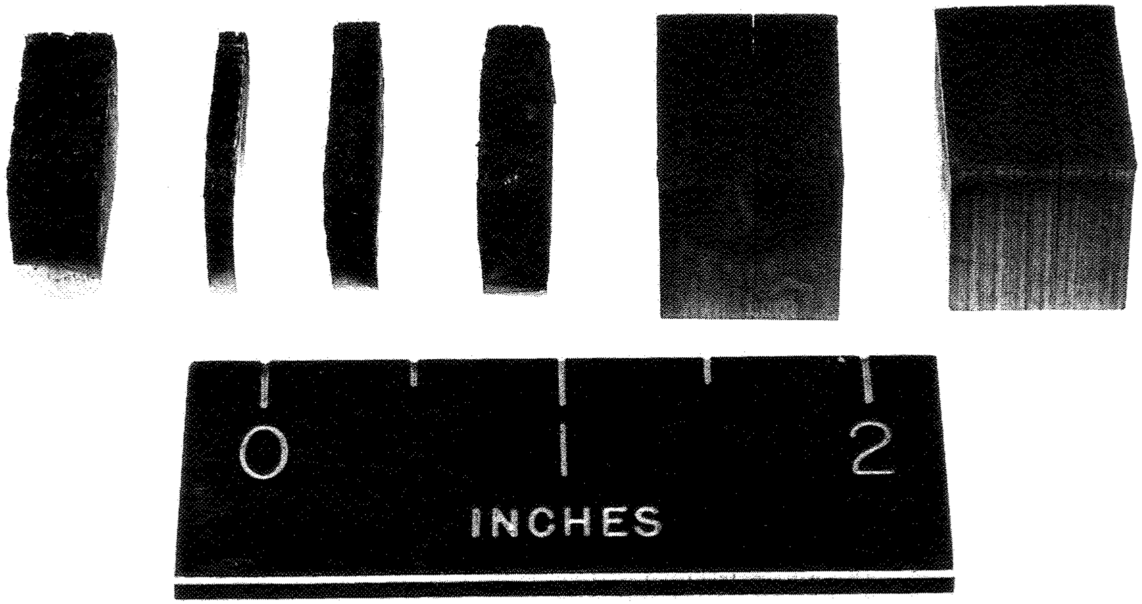
THERMAL SHOCK TEST: HIGH FLUX RATE
15-SECOND RESIDENCE TIME 1-INCH FROM 4000°F QUARTZ LAMPS

Sample Number	Sample Description*	.-Direction Reinforcemenl Density (per in^2)	Damage Description
874-76	Epoxy reference	none	extensive and severe cracks
	Phenolic reference	none	extensive and severe cracks
909-83	Needled fabric No, 2 molded	400 penetrations	cracks
909-75	10-ply tufted fabric cast	64 tufts	cracks
909-10	Needled fabric No. 3 molded	320 penetrations	cracks
909-59	Needled fabric No. 1 cast	400 penetrations	no cracks
909-72	10-ply tufted fabric not reimpregnated	64 tufts	no cracks
909-72	10-ply tufted fabric reimpregnated	64 tufts	no cracks
909-41	Avco 3-D	2400 yarns	no cracks

*More detailed sample descriptions are in Tables V, VI and VII in the data, and the break point is more pronounced. There appears to be no slightly cracked samples: everything tested either showed gross cracks or no cracks. The break point is not nicely defined in terms of fabric geometry, since one tufted fabric, 909-75, failed and one, 909-72, did not. Also a cast needled fabric showed no cracks, though all of the molded needled fabrics cracked as expected. The Avco 3-D sample showed no cracks.

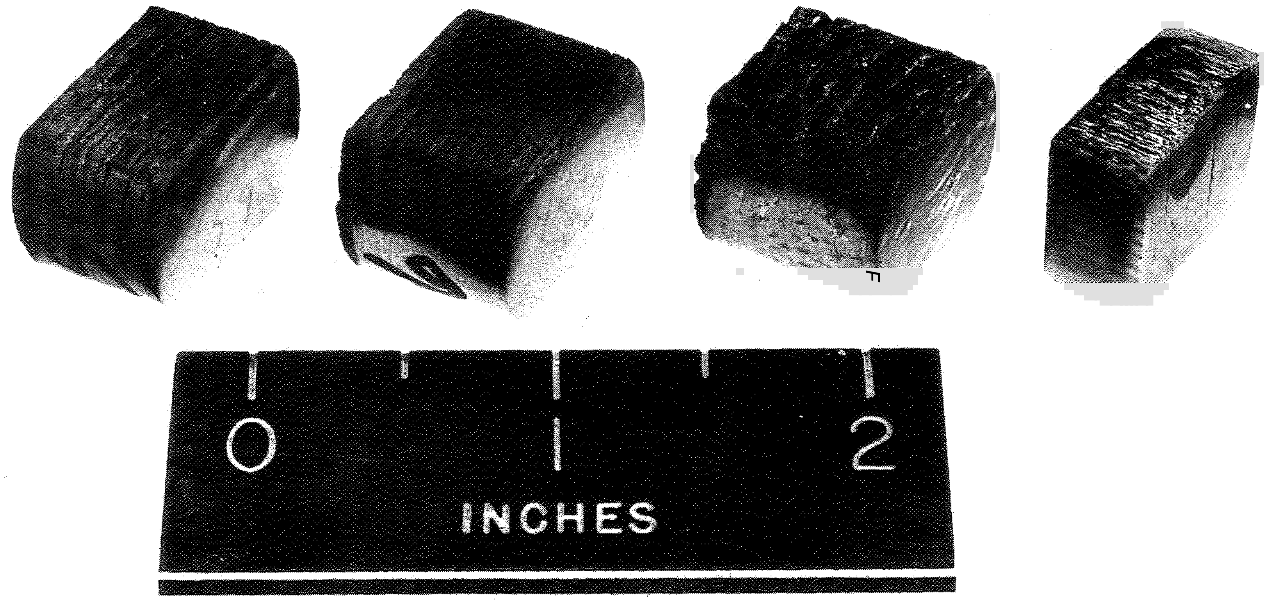
c. High Flux Cyclical Thermal Shock Test

Since both of the previously described tests are only qualitative, and since performance tests for thruster nozzles are on-off tests introducing cyclical thermal stresses, a cyclical heating schedule was set up for the quartz lamp array to give a quantitative value to the thermal shock resistance. The samples were heated for 10 seconds and shielded for 2 minutes 50 seconds, during which time they were examined in place for cracks. This sequence was repeated until all samples had surface cracks. A further refinement included machining all samples to a 5/8-inch thickness, with the interlaminar direction in the plane of the machined surface. The flat machined surface was exposed to the array of quartz lamps. Figures 105 through 109 show pictorially the results of the tests and Table XVIII orders the samples according to the cycles required to produce visible surface cracks. The results suggest that more work needs to be done defining the failure criteria and improving the sensitivity of failure detection. The range of cycles to failure is from 2 to 5, but there is a major difference between the reference material "failures" and all other candidate composite "failures" except the double-loop fabric laminate. The surfaces of both crack, but in the reference laminates and the double-loop fabric laminate the cracks propagate entirely, or almost entirely, through the sample. That is, a crack that develops in the surface char zone propagates through the partially degraded zone beneath the char and through the virgin material as well. The candidate composites, except the double loop, regardless of percentage of Z direction reinforcement, restrict the cracking almost exclusively to the char layer. Again, to emphasize this point, almost no cracks appear in the virgin material in any of the candidate composites, with the exception of the double-loop laminate and the no-lock braid. The candidate composites that survived to 4 or 5 cycles included two needled samples, the double-loop sample, and the Avco 3-D, while two tufted samples were only slightly behind. The Avco 3-D sample showed some swelling in the exposed surface with some question whether the "cracks" that were visible were cracks or areas where resin was burned out of the surface. It appears from these results that the appearance of cracks on or in the surface layer is not a good criterion of failure. The definition of a good failure criteria must await a more detailed study of the test and material parameters. An increase in the flux level may improve the sensitivity of the test and the definition of the failure criteria.



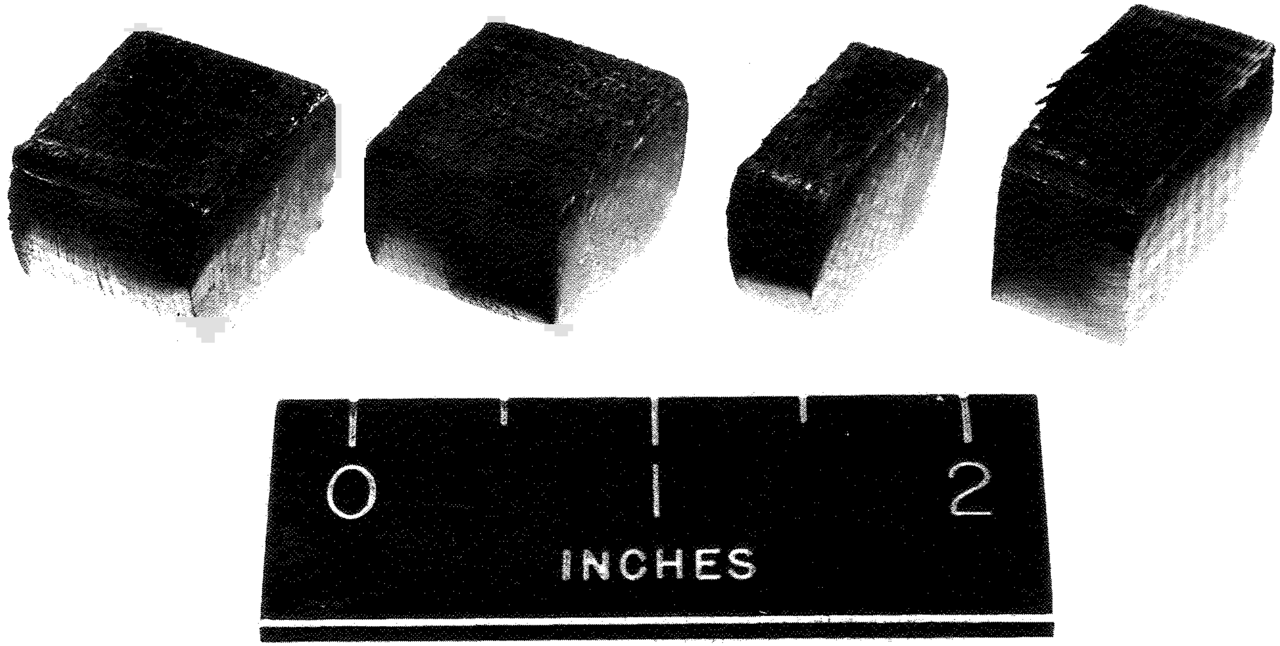
16082C

Figure 105 LEFT TO RIGHT (CYCLIC EXPOSURE): TUFTED, 10-PLY, BACK-TO-BACK (910-8); TUFTED, 14-PLY, (909-62); TUFTED, 10-PLY, (909-75); TUFTED, 10-PLY, RE-IMPREGNATED (909-72); PHENOLIC-GLASS REFERENCE RUN 1; PHENOLIC-GLASS REFERENCE RUN 4



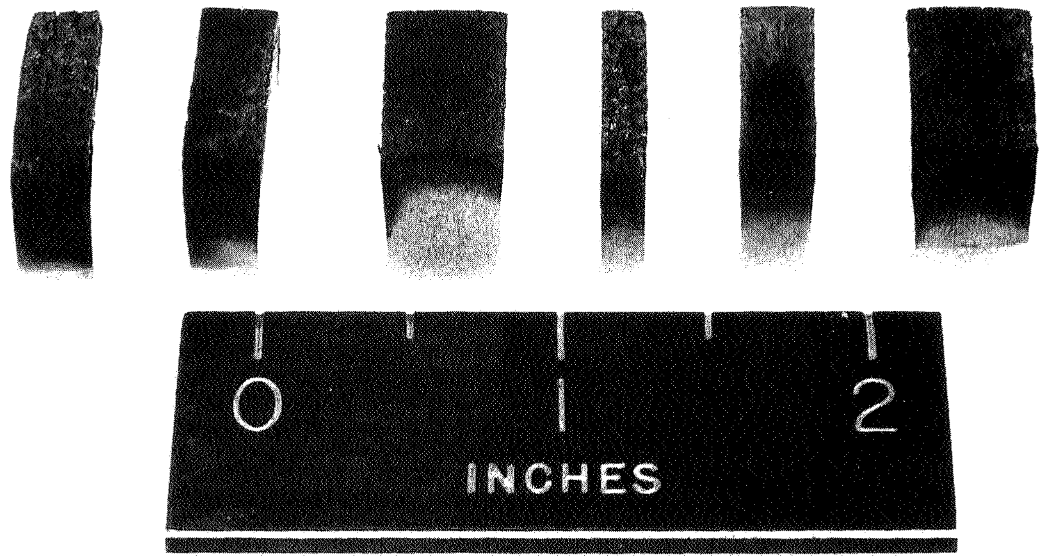
16082A

Figure 106 LEFT TO RIGHT (CYCLIC EXPOSURE): NEEDLED FABRIC NO. 1, CAST (909-59); NEEDLED FABRIC NO. 1, CAST (909-68); NO-LOCK BRAID (909-106); EPOXY-GLASS REFERENCE (874-76)



160828

Figure 107 LEFT TO RIGHT (CYCLIC EXPOSURE): HAND-SEWN LAYERS OF CLOTH (910-9); NEEDLED FABRIC NO. 6, CAST (909-145); NEEDLED FABRIC NO. 3, MOLDED (909-101); AVCO 3-D (909-41)



160820

Figure 108 LEFT TO RIGHT (CYCLIC EXPOSURE): NEEDLED STAPLE FABRIC, CAST (909-114); NEEDLED FABRIC NO. 2, MOLDED (909-85); NEEDLED FABRIC NO. 6, MOLDED (909-148); MULTIPLE WARP (910-10C); NEEDLED FABRIC NO. 3, MOLDED (909-83); NEEDLED FABRIC NO. 6, MOLDED (909-147)

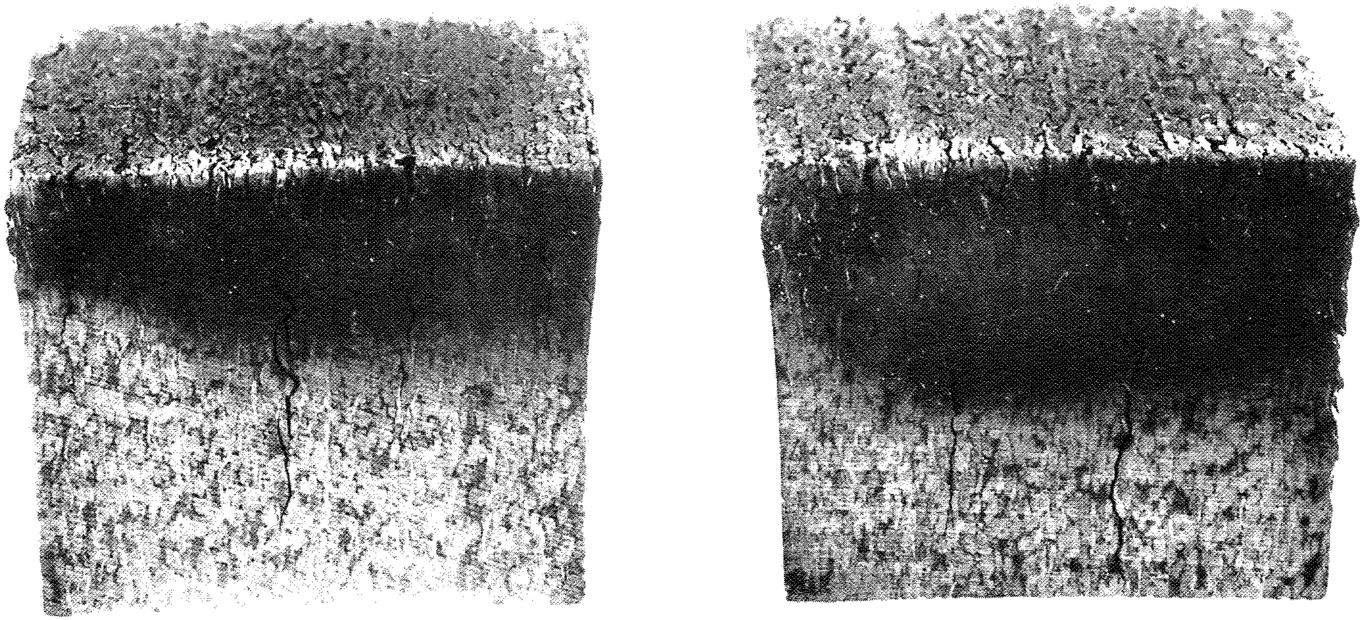


Figure 109 DOUBLE LOOP LAMINATE (4700-1) CYCLIC EXPOSURE

TABLE XVIII

CYCLIC HIGH FLUX THERMAL SHOCK TEST

10-sec residence time, 1-inch from $4000^{\circ}F$ Quartz lamps
2-minute 50 sec cooling time
samples cycled until failure

Sample No.	Description	Z-Direction Reinforcement Density (per in^2)	Cycles to Failure
874-76	epoxy-glass reference	none	2
------	phenolic-glass reference	none	2
------	phenolic-glass reference	none	2
909-106	non-locked braid	none	2
910-10C	Multiple warp		2
909-68	Needled fabric No. 1 cast	400 penetrations	2-1/2
910-9	hand sewn layers of cloth	9-16 threads	2-1/2
909-59	Needled fabric No. 1 cast	400 penetrations	3
909-147	Needled fabric No. 6 molded	1400 penetrations	3
909-75	10-ply tufted fabric cast	64 tufts	3
909-101	Needled fabric No. 3 molded	320 penetrations	3
910-8	10-ply tufted fabric	64 tufts	3 t
909-145	Needled fabric No. 6 cast	1400 penetrations	3+
909-62	14-ply tufted fabric cast	64 tufts	3 t
909-72	10-ply tufted fabric reimpregnated	64 tufts	3-1/2
909-148	Needled fabric No. 6 molded	1400 penetrations	4
478-20-1	Double loop fabric laminate	169 loops	4 t
909-85	Needled fabric No. 2 molded	400 penetrations	5
909-83	Needled fabric No. 2 molded	400 penetrations	5
909-114	Staple fiber needled matt	unknown	5 t
909-41	Avco 3-D	2400 yarns	5 t

t indicates only slight crack(s) at end of cycle

1/2 indicates questionable crack(s) at end of cycle definite cracks at end of next cycle

NOTE: At end of test, only reference materials and double-loop fabric laminate showed cracks into uncharred material. Cracks in reference materials went completely through or almost completely through 5/8 inch thickness of test specimen. Although the cracks in the double-loop fabric laminate went into uncharred material, the cracked specimens still held together strongly where the epoxy reference fell apart, and the phenolic reference could be separated at the crack with light pressure.

d. Original Thermal Shock Tests

Originally, two other types of thermal tests were to be conducted. Previously, the Mechanical Evaluation Group had applied radio frequency dielectric heating techniques in order to rapidly raise the temperature of test samples. Because conducting metals cannot be placed in the magnetic field, devising a thermal shock test is not a straight forward routine matter. Thus the existing Avco RAD high-temperature resistance heating facility was suggested for the thermal shock experimentation. These tests would have been performed as follows:

1) Sharp thermal gradients would be imposed across the thickness of 3- x 3- x 1/4-inch plates in order to induce interlaminar shear failures. The temperature profile would be achieved by placing one face of the plate against a thin tungsten sheet that had previously been raised to high temperature. Tests would be conducted to determine the conditions necessary to cause failure both in typical laminates and in the prime-candidate three-dimensionally-reinforced plastic system.

2) Tubular samples would be positioned over a solid cylindrical tungsten heating core and restrained axially between rigid load platens. By simultaneously restricting axial motion and rapidly heating the tungsten heating element, gross failures would be induced in the 3-D composites, and comparison of the performance of the various materials could be made on the basis of observed temperature profiles and required restraining forces.

D. TEST CHAMBER FABRICATION

1. Fabric Data

As an initial step towards developing a correlation between the mechanical and thermal test results and actual thruster performance, three test chambers were fabricated, In the test facility the chamber mates to an injector on one end and a water cooled throat on the other end. The chambers were made of quartz thread woven into Avco 3-D fabric. The fabric geometries and the chamber orientation relative to the fiber axis were varied to give the following samples.

a) Standard weave (Cartesian coordinate) with 2000 threads/in^2 in the X + Y directions and 2400 threads/in^2 in the Z direction, The axis of the chamber is in the Z direction. Figure 110 left shows the side of the chamber: The injector end is at the top and the Z axis of the fabric block is vertical. The two recesses on the cylindrical surface are for the split rings, to which the injector and water cooled throat components are bolted. Figure 110 right shows a view of the end that is bolted to the injector apparatus, The recess is for an o-ring seal, and the small hole is for a chamber pressure tap.

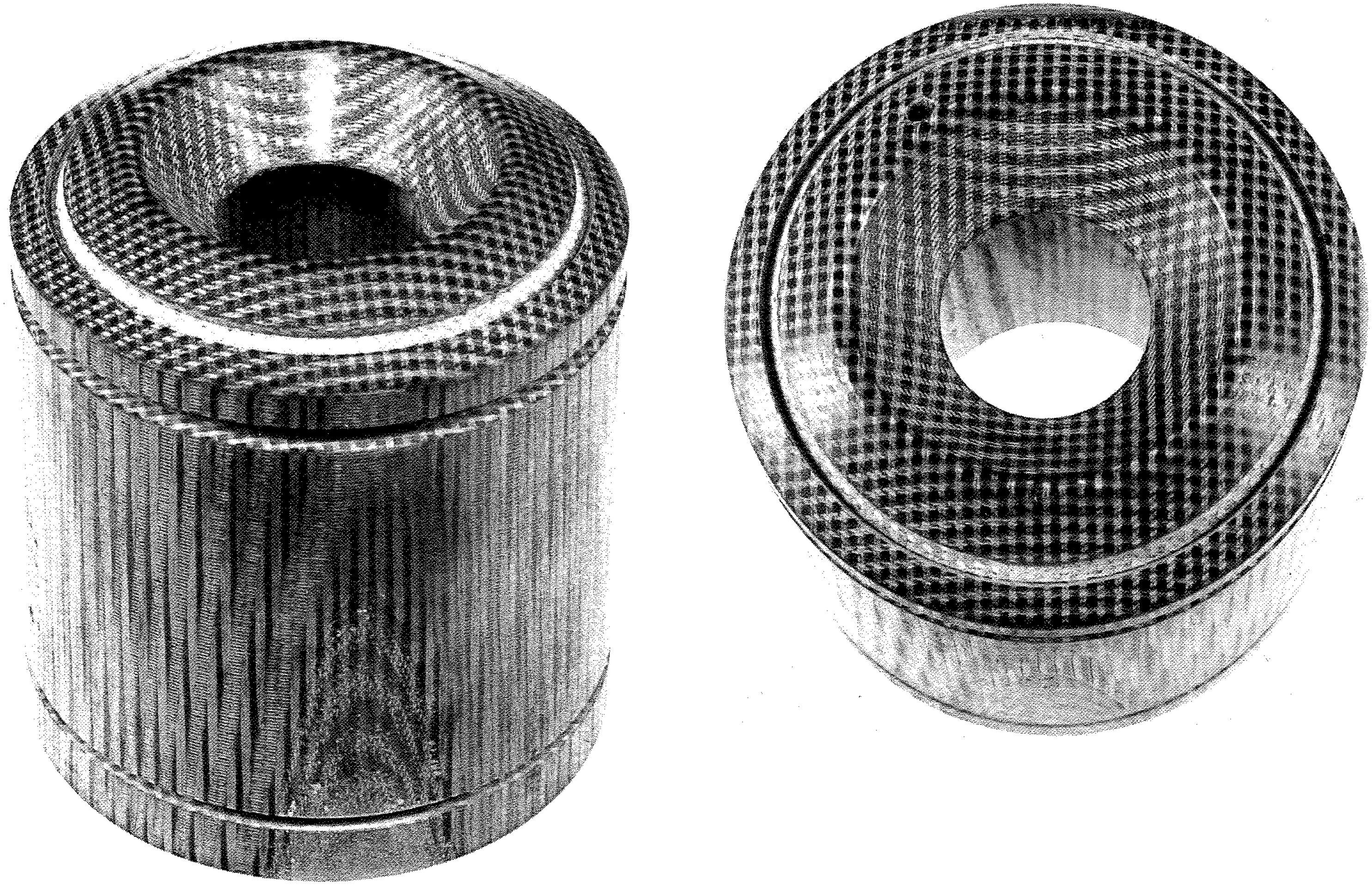


Figure 110 SIDE VIEW AND END VIEW OF CHAMBER NO. 1

b) Standard weave plus threads in both 45 degree directions in the X, Y plane. There are 1000 threads per square inch in the X + Y directions, 1300 threads per square inch in the 45-degree directions, and 2400 threads per square inch in the Z direction. The axis of the chamber is in the Z direction. Figure 111 shows the chamber from the side view, and again the injector end is at the top, with the Z axis of the fabric block vertical. The large patch of horizontal threads on the front portion of the cylindrical surface is part of the selvage formed when weaving with the 45-degree threads. Figure 112 is an injector end view and shows the X - Y pattern of threads quite clearly. While there is some distortion of the pattern, threads can be seen that are oriented in each of four directions. The small hole on the right side is the chamber pressure tap.

c) Standard weave with 2000 threads per square inch in the X + Y directions and 2400 threads per square inch in the Z direction. The axis of this chamber is in the cube diagonal, The side view of the chamber is shown in Figure 113, with the injector end at the top. The Z axis of the block, however, is now at 45-degrees from the chamber axis of the photo but tipped forward at the top. Since the wide chamber surface is parallel to the outside, one can see plainly that only very short pieces of reinforcement lie in the plane of the surface. Most are tied deep into the wall, which should prevent spallation as a mode of surface failure. Figure 114 shows the injector end with the chamber pressure tap.

These combinations of thread geometry and chamber orientation will provide preliminary information on the effect of fabric geometry on firing performance.

The three fabric blocks were impregnated with, first, phenolic and, then, epoxy resins to give high ablative performance, low porosity composites. Each impregnation was done slightly differently: As problems due to block size and thread geometry were observed, the procedures for a subsequent block were modified to reduce,or eliminate, the problems. These variations are described next.

2. Impregnation Data

The samples were evacuated in a vacuum chamber for 2 hours at 150°F at 0. 3 mm mercury. Methyl alcohol was introduced under vacuum, and the samples were allowed to soak several hours at 150°F at atmospheric pressure. The excess alcohol was then removed from the container, and the samples were again evacuated for 2 hours at 150°F at 0.3 mm mercury. Phenolic resin (Monsanto SC1008) was reduced to a specific gravity of 1. 075 with methyl alcohol and heated to 150°F. The preheated resin was

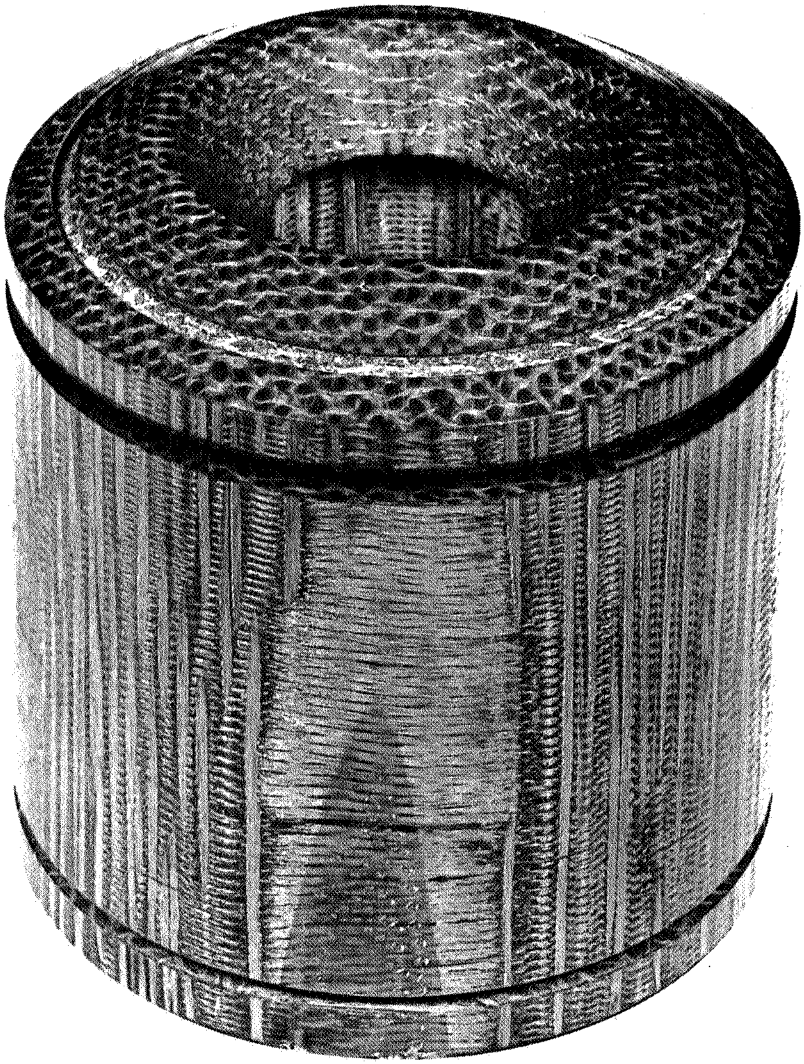


Figure 111 SIDE VIEW OF CHAMBER N0.2

Figure 112 END VIEW OF CHAMBER N0.2

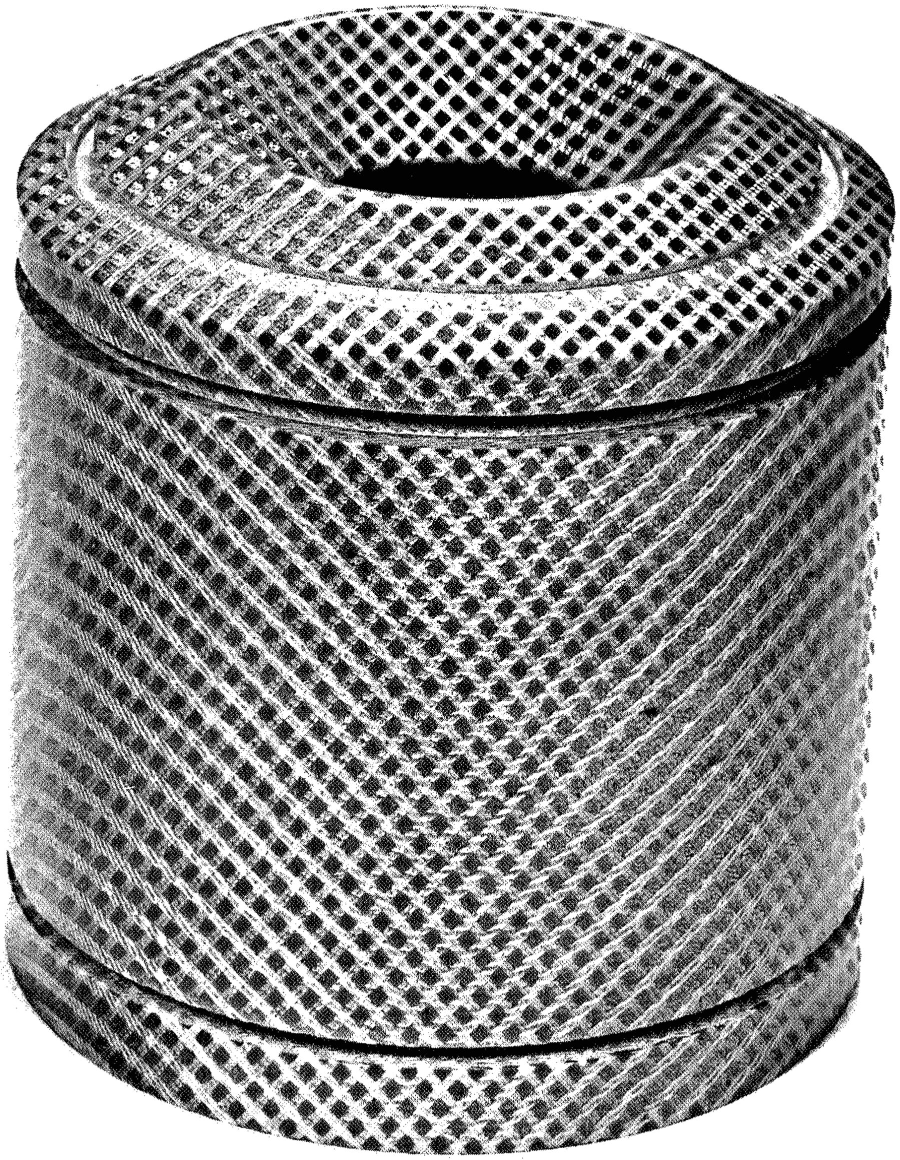


Figure 113 SIDE VIEW OF CHAMBER NO.3

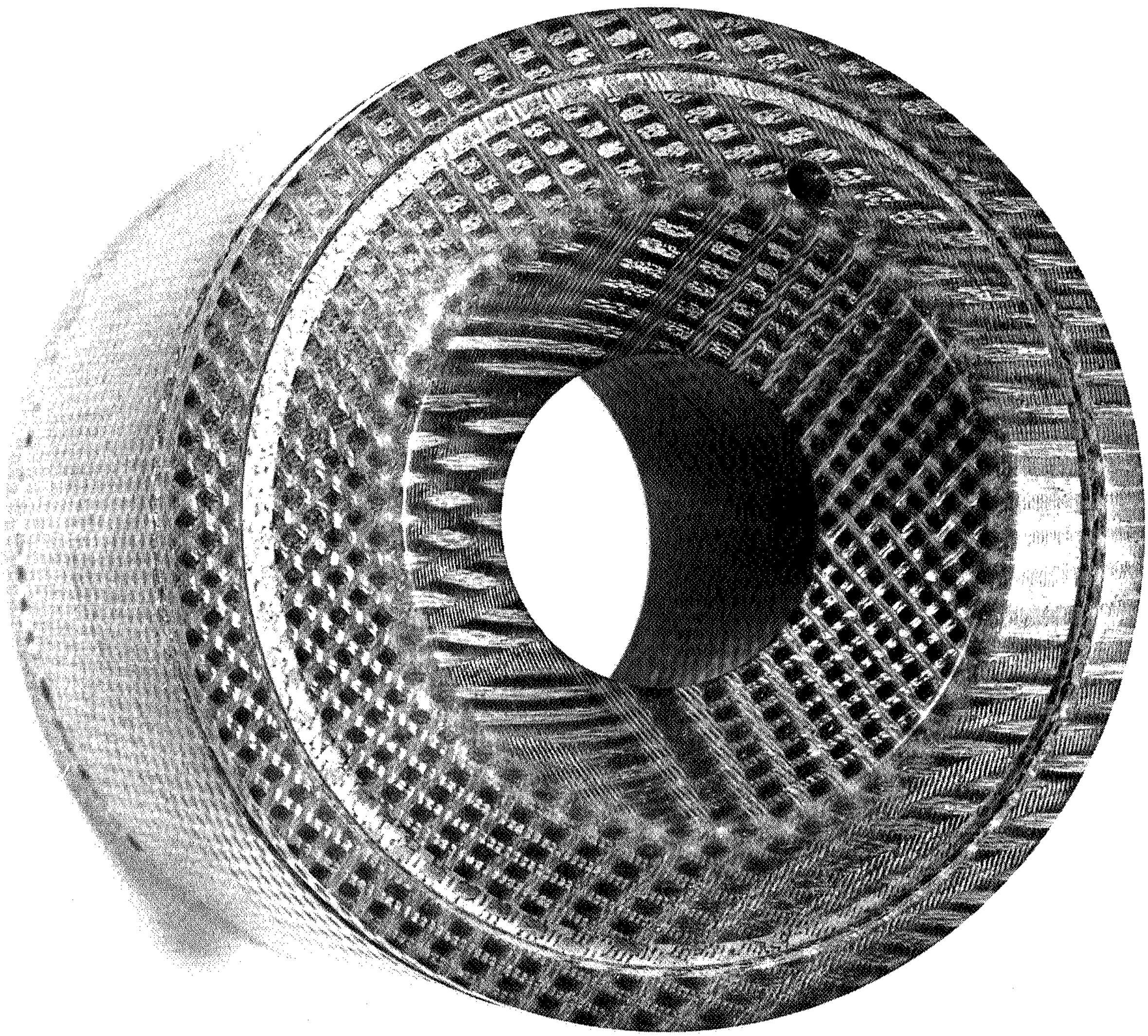


Figure 114 END VIEW OF CHAMBER N0.3

then introduced into the sample under vacuum, and the evacuation continued for 1 hour at 150°F. After 1 hour, the vacuum was relieved, and the samples were allowed to soak overnight (approximately 16 hours) at room temperature in the phenolic resin. At the end of the soak period, the resin and samples were again heated to 150°F and placed in a pressure vessel. The samples were then pressurized at 300 psi under nitrogen. The pressure was relieved every 15 minutes and reapplied, This was repeated five times. The samples were removed from the resin at the end of the pressure cycle and placed in a 150°F air circulating oven overnight for "B-staging." The "B-staging" was then followed by a vacuum postcure, going from 200°to 325°F in 20 hours, and 325" to 350°F in four hours.

Epoxy Impregnation

Resin System	Parts by Weight
Den 438	200
Nadic Methyl Anhydride	225
Celluflex FR2	20
Phenyl Glycidol Ether	50
DMP 30	1

Before the samples were impregnated with the epoxy resin system, the surfaces were ground to open the pores that became crusted over with phenolic resin during the cure, This surface material removal resulted in block 1 and 2 being too small by about 1/16–1/8 inch for the finished chamber dimensions. Before turning to dimensions, these blocks had enough epoxy-glass cloth layers added and cured to return the blocks to the right size. The samples were then evacuated at 200°F at 0.3mm mercury. The resin system components were heated to 200°F and mixed immediately before the system was introduced into the samples under vacuum. The evacuation was continued for 1 hour at 200°F. The vacuum was then relieved and the samples placed in a pressure vessel for pressurizing at 300 psi under nitrogen. The pressure was relieved every 15 minutes and reapplied. This was repeated five times. Following the pressure cycle, the samples were left in the resin and cured in an air circulating oven for 4 hours at 240°F, and 16 hours at 300°F. After cure, the samples were chipped free of the excess resin.

Sample No. 104 received one phenolic impregnation followed by an epoxy impregnation. Impregnation appeared normal at all stages. Sample No. 107 received one phenolic impregnation followed by two epoxy impregnations. Bulk density appeared low after first epoxy impregnation, so a second was done. Sample No. 121 received two phenolic impregnations followed by a single epoxy impregnation, Resin content after first phenolic impregnation was too low (<20 percent), so a second phenolic impregnation was done.

Table XIX lists the data on these samples.

TABLE XIX

Block No.	Sample No.	Woven Density	Phenolic Resin Content (percent)	Density Phenolic Impregnation	Total Resin Content (percent)	Final Density
1	104	1.27	25. 2	1. 35	37.4	1. 77
2	107	1. 11	21. 1	1.45	34. 2	1. 74
3	121	1.10	28. 1	1. 52	34. 8	1. 73

The second block (standard weave and both 45's in X, Y plane) was impregnated with less success than the first block. The bulk density is slightly lower at 1. 74 than block 1 and, X-ray photographs (compare figures 115, 116, 118, and 119) show some voids along the Z direction fibers. Some of these voids are indicated by arrows in Figure 118. Block 2 was cored, and there was a series of voids along some of the vertical (Z direction) reinforcement. Since both blocks were impregnated in identical fashion, it appears that the 45-degree yarns may prevent complete impregnation in large blocks. The geometry of the resin paths is probably the source of this difficulty. In the standard weave, apparently the resin can follow an X or Y thread to the center of the block quite easily. The standard weave has an equal number of threads in each of the X and Y directions, so that at the cross-over point of an X and Y thread there is a predominate tendency for the resin to continue wicking along the original thread, rather than divert to the cross thread. The resin has to go through a higher resistance narrow slot to change to the other thread, so that with the cross-sectional area of each thread the same, the flow along the initial thread predominates. In the 45-degree block, however, there are three times as many threads trying to divert the flow, and, thus, continuous wicking along the same thread may no longer predominate.

Block 104 std. weave

Figure 115 DIRECTION Z RADIOGRAPH OF BLOCK NO. 1 AFTER PHENOLIC IMPREGNATION

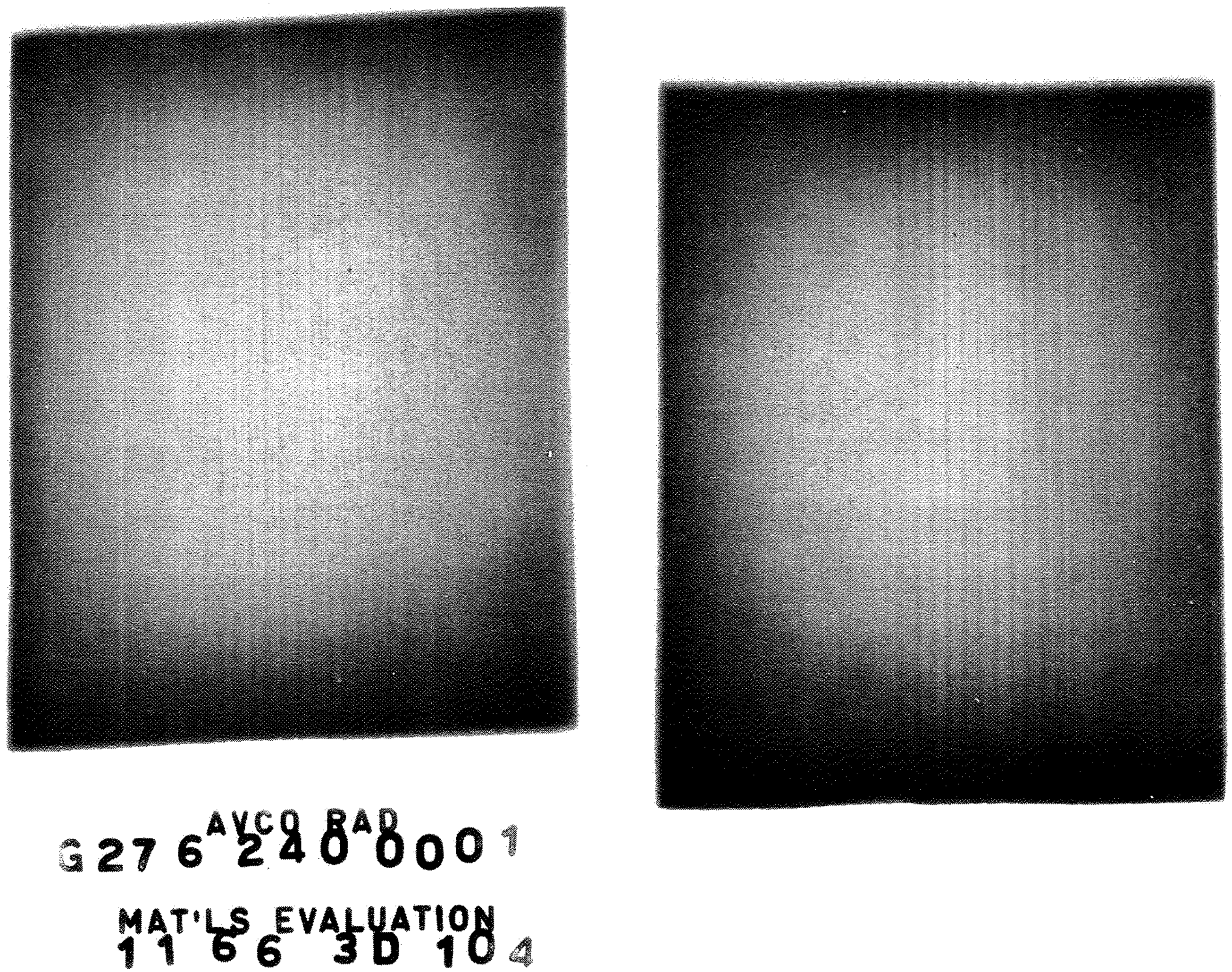


Figure 116 DIRECTION X + Y RADIOGRAPH OF BLOCK NO. 1 AFTER PHENOLIC IMPREGNATION

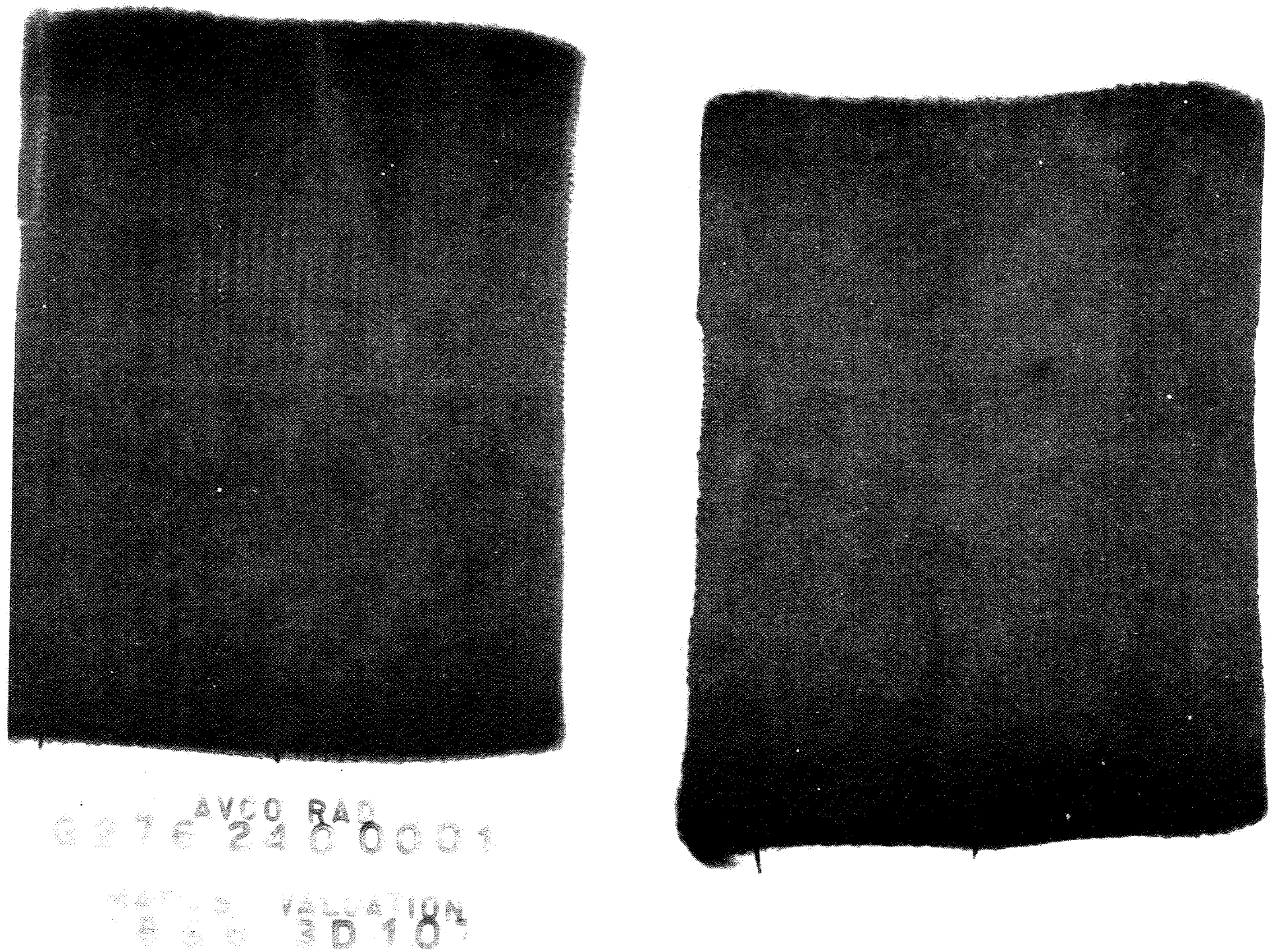


Figure 117 DIRECTION X + Y RADIOGRAPH OF BLOCK NO 2 AS DRY FABRIC

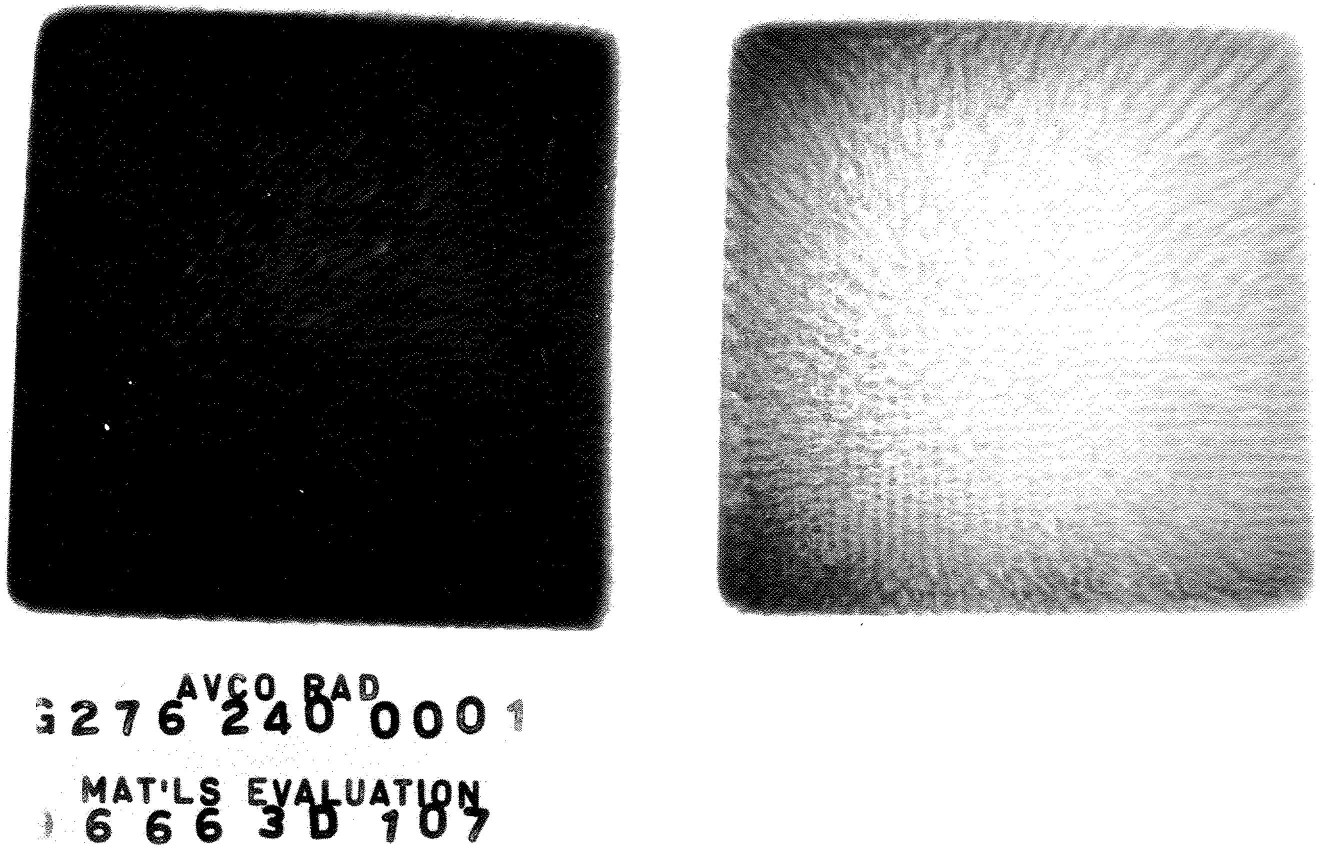


Figure 118 DIRECTION Z RADIOGRAPH OF BLOCK NO. 2 AFTER PHENOLIC IMPREGNATION TWO EXPOSURES

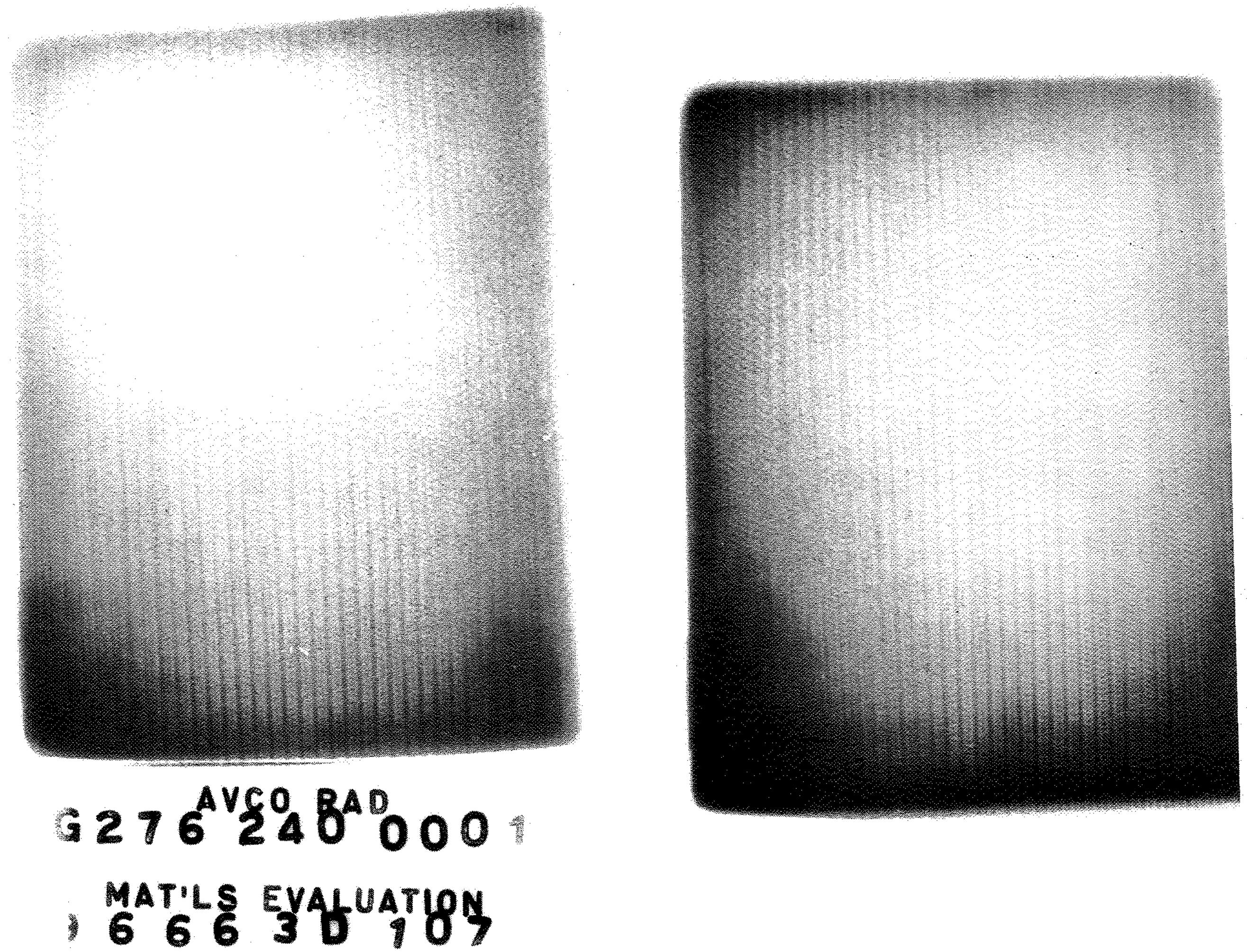


Figure 119 DIRECTION X + Y RADIOGRAPH OF BLOCK NO 2 AFTER PHENOLIC IMPREGNATION TWO EXPOSURES

Regardless of whether this theory operates, the cored sample was reimpregnated and the voids eliminated, since they are open to a surface as a result of the coring. After re-impregnation, the block was X-rayed again and found to be void free. (See Figure 120 and 121.)

The third block was 50-percent larger in each linear dimension, and, inadvertently, sufficient extra time was not allowed during the first phenolic impregnation to give a resin content as high as that in Block No. 1. For this reason, the block was given a second phenolic impregnation. Figure 122 shows a Z direction radiograph of the dry block and indicates that all Z direction threads are in place. Figures 124 and 126 appear to show a density difference from the edge of the block to the center. The darker edges indicate that the incident X-ray beam is attenuated more at the edges than in the center, This may be partly an artifact from the geometry of the X-ray system but is more likely a function of the flow time for the resin to get to the center of the block. The final epoxy impregnation was done on a cored rough machined piece, A comparison of Figures 118 and 120 for Block No. 2, the'final epoxy impregnation was done on a cored sample, indicates that the density gradient is substantially reduced.

3. Chamber Modifications

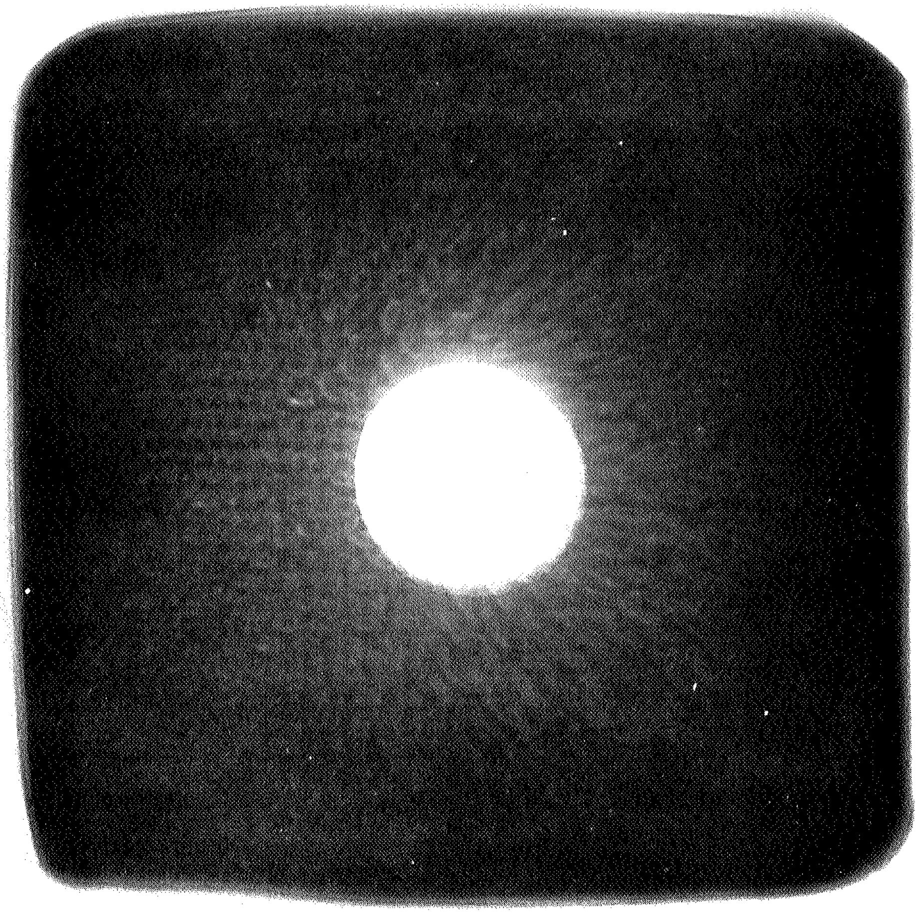
The chambers were machined to the dimensions given in Drawings SK108231 (Liner, head end: capillary injector evaluation) and SK108242 (Liner, . ablative chamber evaluation), The chamber was modified so that the head end injector and liner were made in a single piece. The single piece eliminates a weak spot in the wall and allows the injector and water-cooled throat to be tied to the experimental chamber separately, through the use of split rings. This method of attachment results in a more severe test of the chamber, since the thermal stresses from heating and cooling are no longer taken by the metallic jacket, The greatly superior interlaminar strength and thermal shock resistance of the Avco 3-D reinforced composites allow such a design and test procedure. All machining was done with diamond tools, and then the inside surface was polished with emery paper so that wall-initiated turbulence would be minimized.

E. THRUSTER FABRICATION DESIGN

1. Three-Step Comb Method

The present state-of-the-art of three dimensionally reinforced composite cylinders and cones is such that the radial fibers are rather difficult to orient during the fabrication operation. The present technique is as follows:

The circumferential and longitudinal fibers are first laid on a cylindrical mandrel that is especially prepared to leave voids in the wrapping for the later insertion of fibrous radial elements. These voids are prepared by



AVCO RAD
G276 240 0001

MAT'LS EVALUATION
9 12 66 3D10

Block 107 std. weave + 2-45° in x-y plane

Figure **120** DIRECTION Z RADIOGRAPH OF BLOCK N0.2 AFTER EPOXY RE-IMPREGNATION

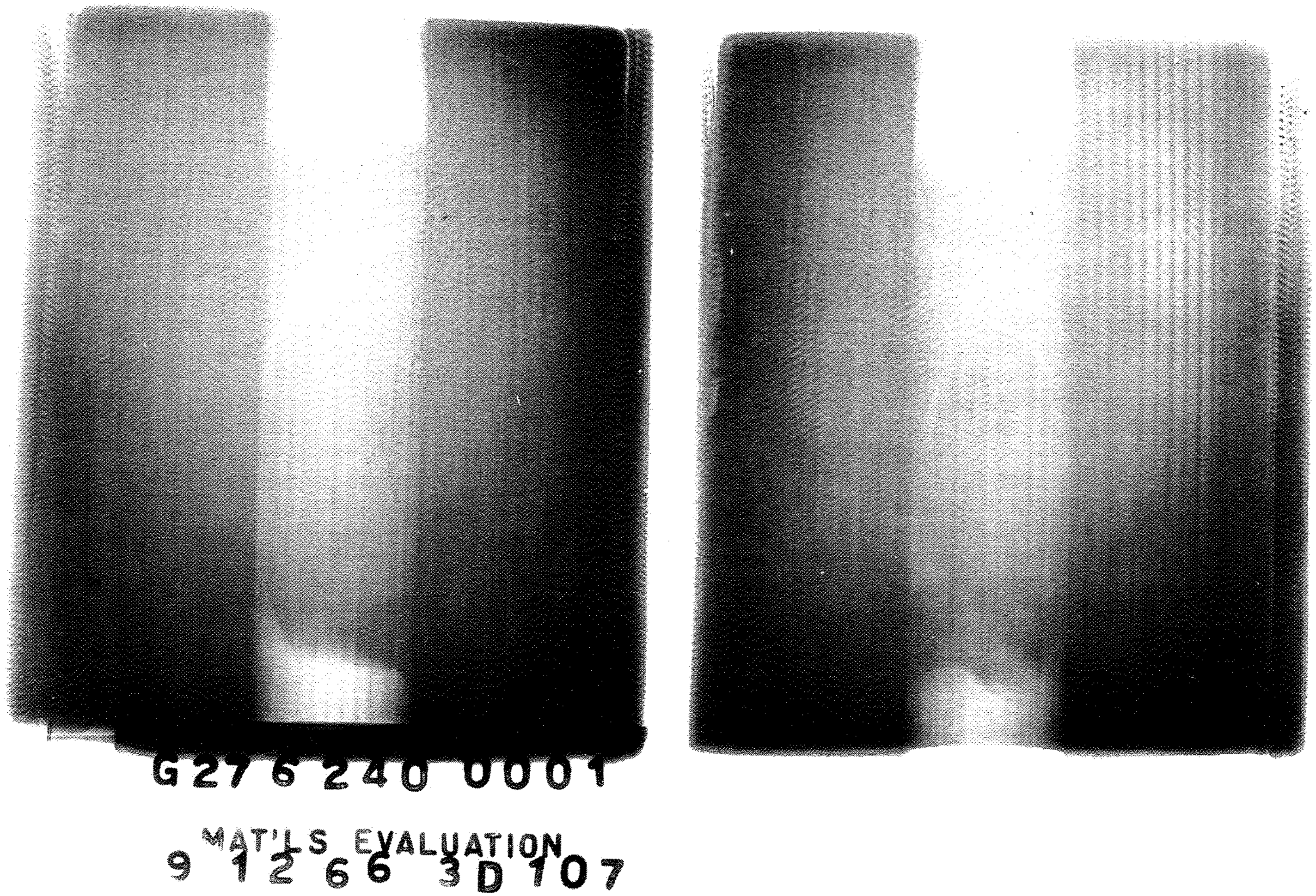


Figure 121 DIRECTION X + Y RADIOGRAPH OF BLOCK NO 2 AFTER EPOXY RE-IMPREGNATION

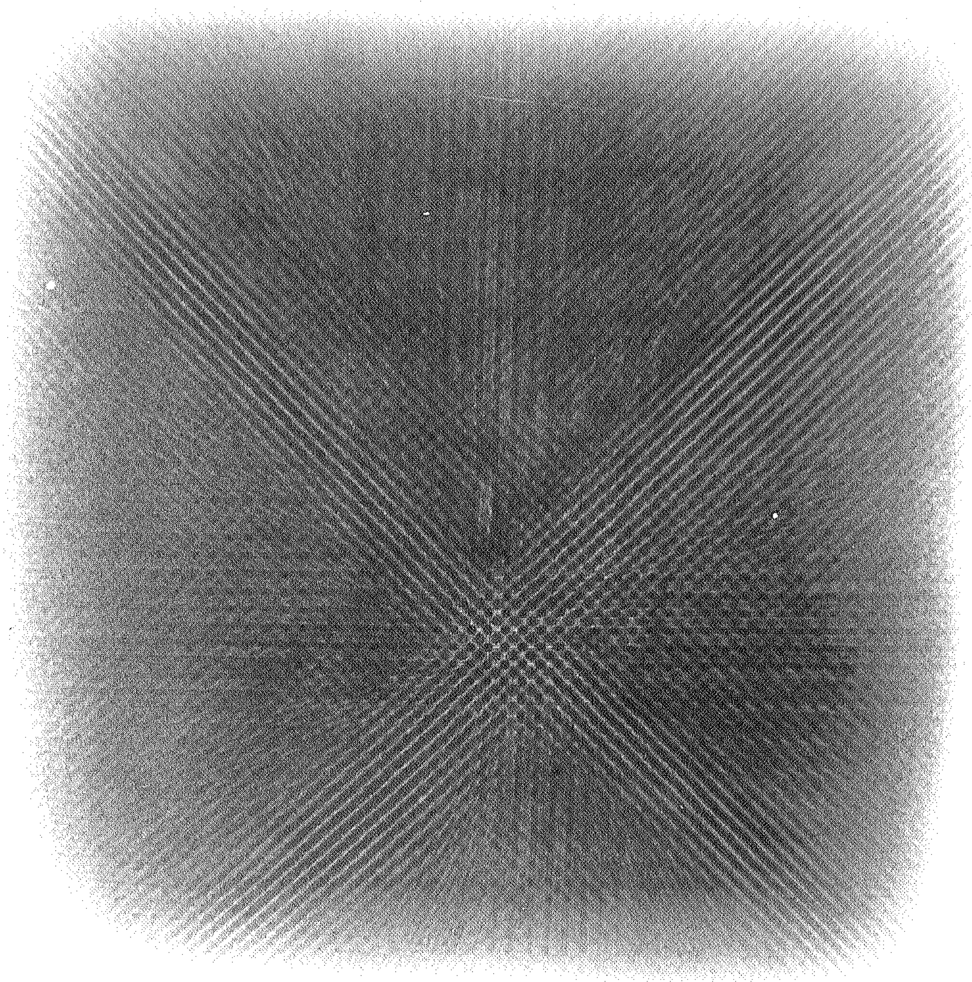


Figure 122 DIRECTION **Z** RADIOGRAPH OF BLOCK NO. 3 IN **DRY** CONDITION

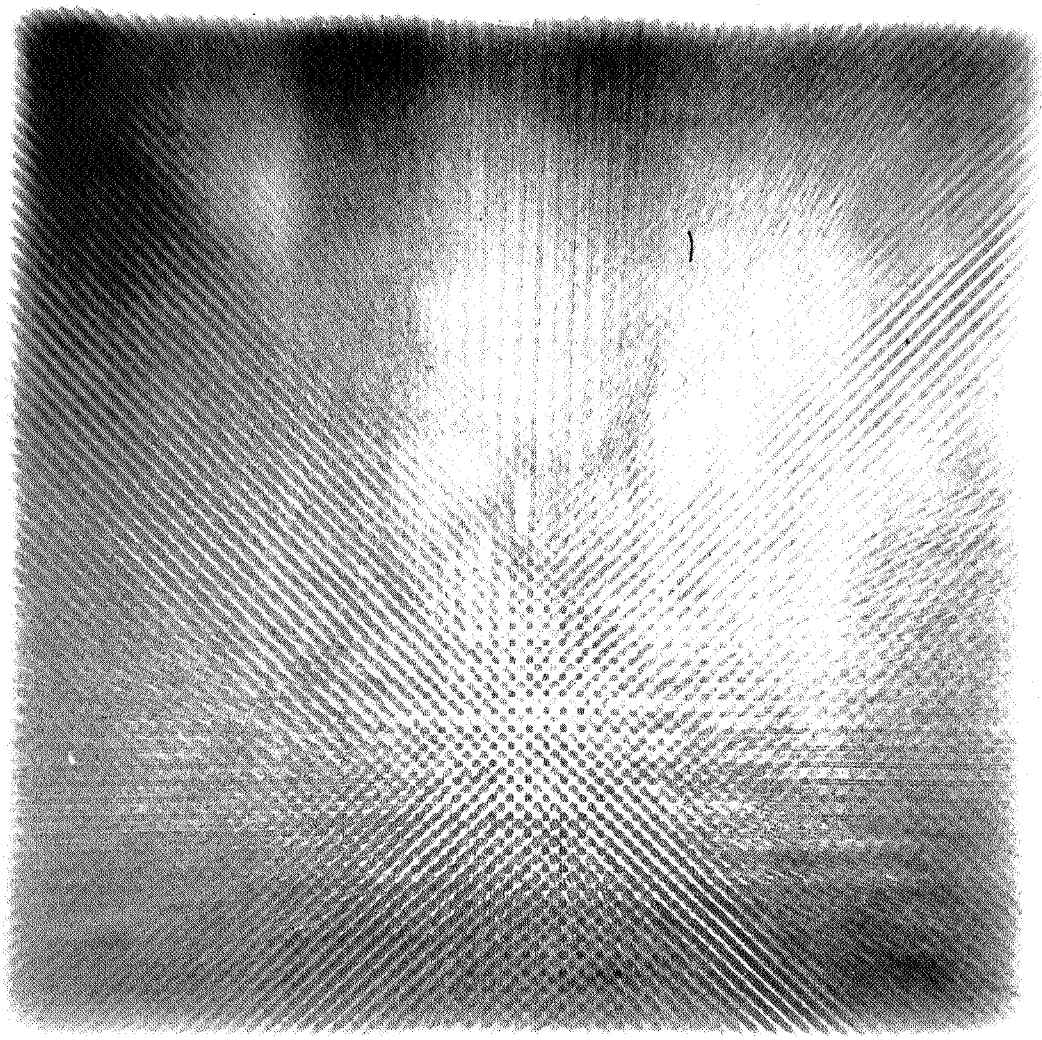


Figure 123 DIRECTION Z RADIOGRAPH OF BLOCK NO. 3 AFTER 1ST PHENOLIC IMPREGNATION

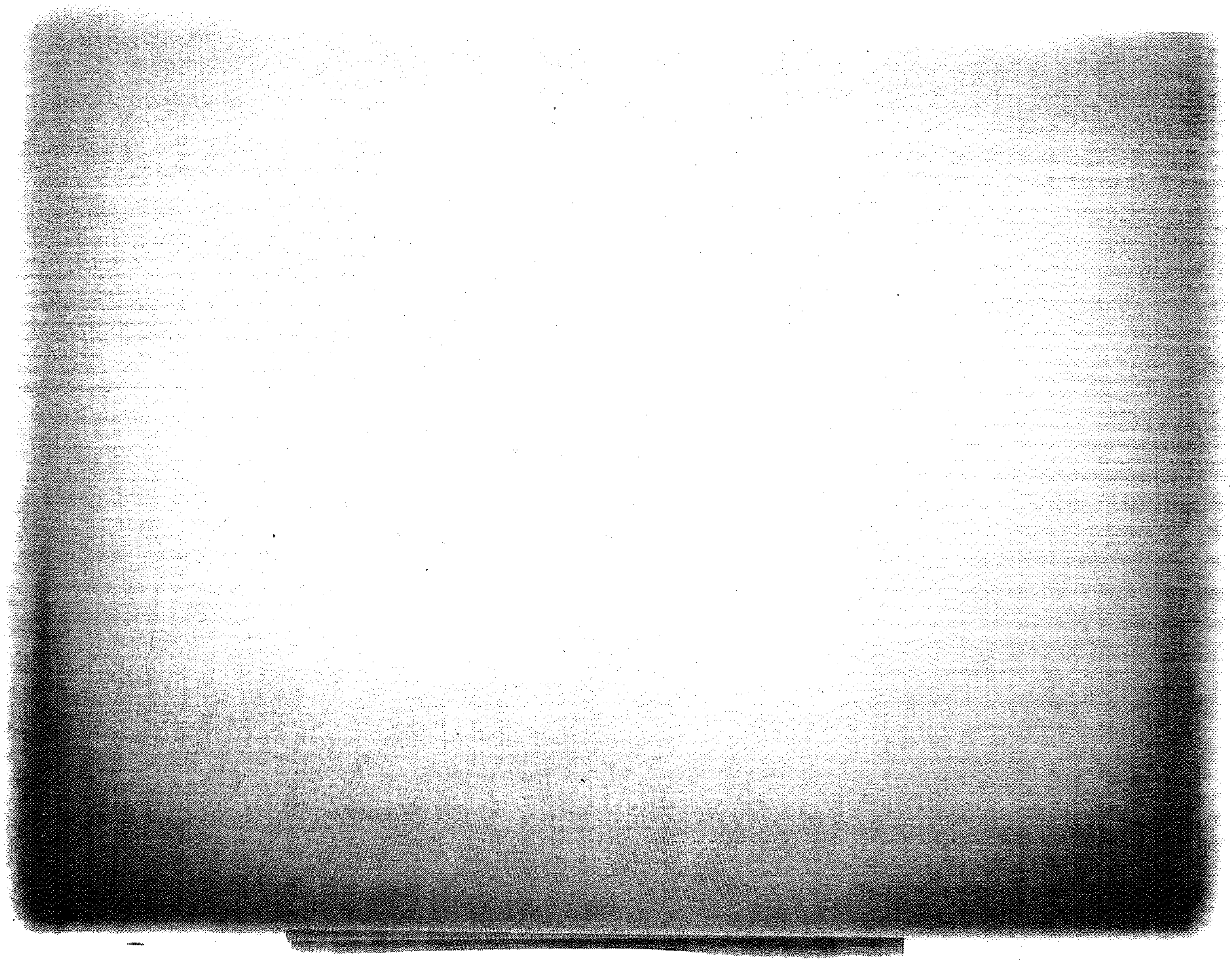


Figure 124 DIRECTION X + Y RADIOGRAPH OF BLOCK NO. 3 AFTER 1ST PHENOLIC IMPREGNATION

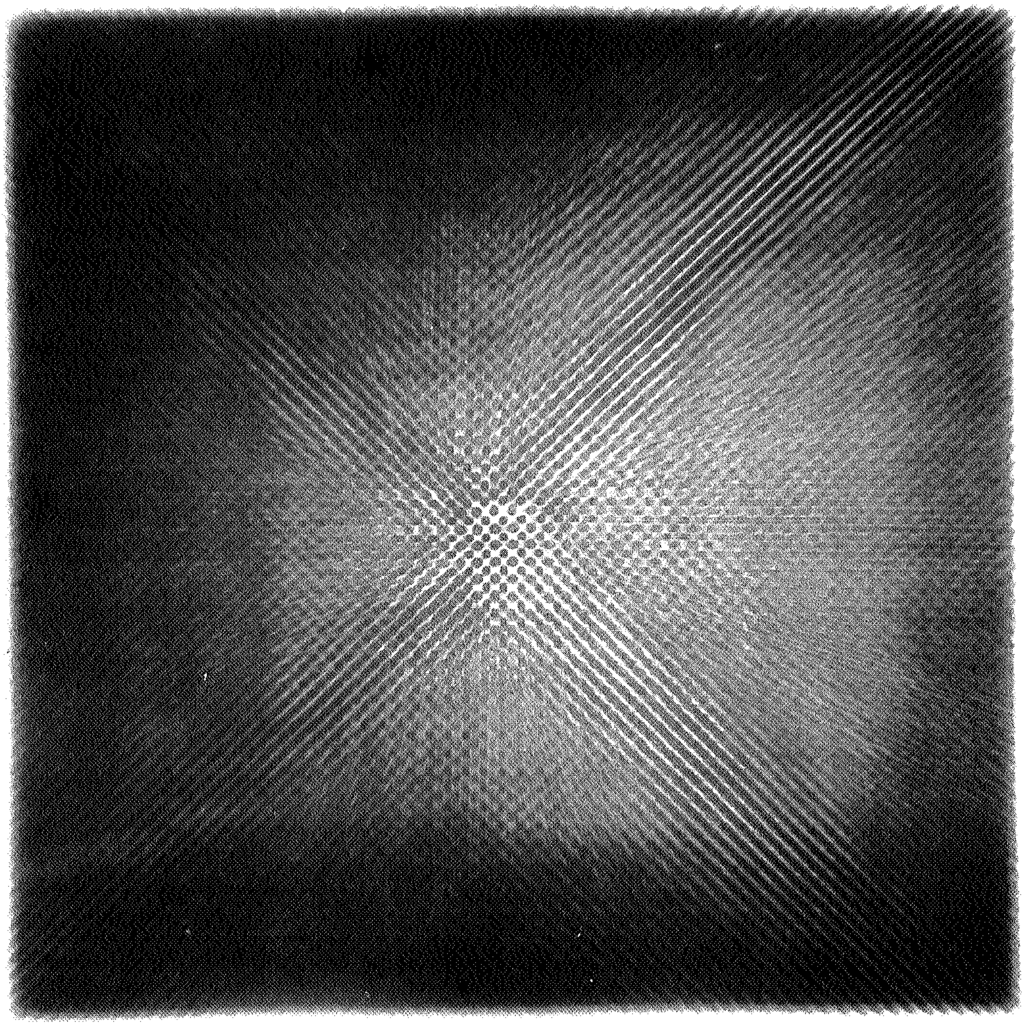


Figure 125 DIRECTION Z RADIOGRAPH OF BLOCK NO. 3 AFTER 2ND PHENOLIC IMPREGNATION

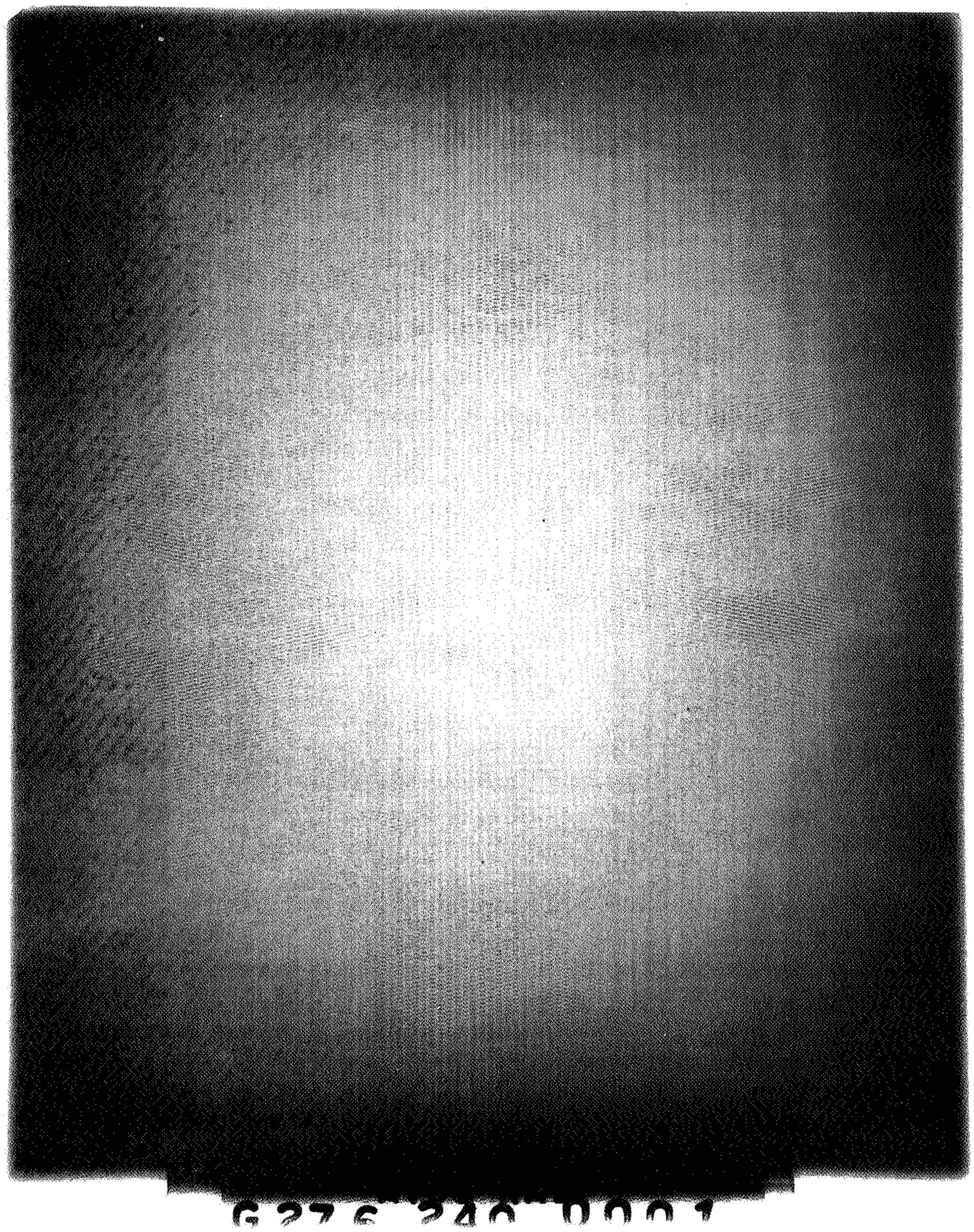


Figure 126 DIRECTION X + Y RADIOGRAPH OF BLOCK NO. 3 AFTER 2ND PHENOLIC IMPREGNATION

including in the mandrel round pins that mount in round holes radially spaced and oriented at the desired location. The circumferential and longitudinal fibers are wrapped around and along the mandrel, being guided by the round pins. After wrapping has been completed, the round pins are withdrawn and fibrous rods of a square cross-section are substituted in the slightly rounded cavities of the wrapping, and the cavities then assume the more square configuration of the rods. For multiple production, this technique becomes laborious, and it appeared advisable to consider some other methods.

Four important problems are to be highlighted:

a) The large number of consecutive man hours required on a unit mandrel assembly.

b) The high cost of mandrel tooling.

c) The necessity of drilling round pin holes in the mandrel and the consequent winding using round interim pins prior to insertion of the square rods.

d) The insertion of the final radial rods in a pre-wrapped cylinder.

e) Relative inflexibility of design after tooling has been fabricated.

Considering these points in turn:

a. One solution is to break up the assembly operation into a number of identical sub-assemblies, allowing a number of sub-assemblies to be assembled simultaneously, thereby reducing the calendar operation time.

b. and c. A typical mandrel has at least 20,000 separate rod holes, a considerable quantity, Since these holes should not be round, but square, and since they are only temporary, their complete elimination would be quite advantageous. Their elimination would also greatly alleviate cylinder removal after wrapping,

d. Final rod insertion is a step that belongs in the original assembly prior to any wrapping, since wrapping should be done on the fibrous rods themselves.

e. Design flexibility should be maintained if possible even after tooling. This can only be done if the tooling is cheap and expendable. This should be a major objective. The following is suggested:

Consider an end view of a wrapped cylinder, each rod defining a radial region. If 180 rods per circumference are used, this region is 2 degrees wide for each rod (360 degrees/180 = 2 degrees) and is shaped like a piece of pie, the rod pointing out radially from the circumference. A sketch of the potted comb is shown in Figure 127, and a completed comb to be used for a conical part is shown in Figure 128.

Successive rods down the length of the cylinder lie in a row, in an identical radial position. In fact, the 2-degree region identified with a rod could be thought of as an end view of a comb, with the rods arranged around the cylinder axis prior to wrapping. The fibrous rods can be permanently assembled in the comb by a potting technique, allowing wrapping to be done on the square rods directly, The potting die is shaped so as to mold the radial pie shaped wedge automatically and also to correctly aline the square rods. The teeth or rods of the comb become the radials of the 3-D cylinder, and the base of the comb, when placed adjacent radially with the other combs, becomes the potted mandrel that is the base structure during fabrication. This base material would be machined out after final processing.

These combs would be normally mounted on a solid cylinder or bar during wrapping. This mounting would be such that the combs could be located in relation to each other to form a helical pattern for filament winding if required. In this case, one end of the mounting cylinder is helically machined as shown in Figure 129, and the combs are moved longitudinally to butt against the helix, which then allows the rods to form a helical pattern.

The same technique could be used to form the complex radially symmetrical shapes of a rocket nozzle and chamber.

One way we have considered to get around the problem of filling in the back of the throat insert with filament winding is shown in Figure 92. Thus, the ablative part of the motor would be made in three phases:

1) Filament wind region marked 1 (Figure 130) behind the throat insert.

2) Weave region marked 2 with combs and prepregged threads. "B-stage" this and machine inside of combs away to profile of filament region I and metallic throat insert.

3) Weave region 3 on combs set up at either end of phase two. This weaving will make the combined piece a single monolithic structure with the reinforcement orientation based on cylindrical coordinates.

Figure 131 will be used to describe the expected steps in the production of .a full-scale thruster with integral throat.

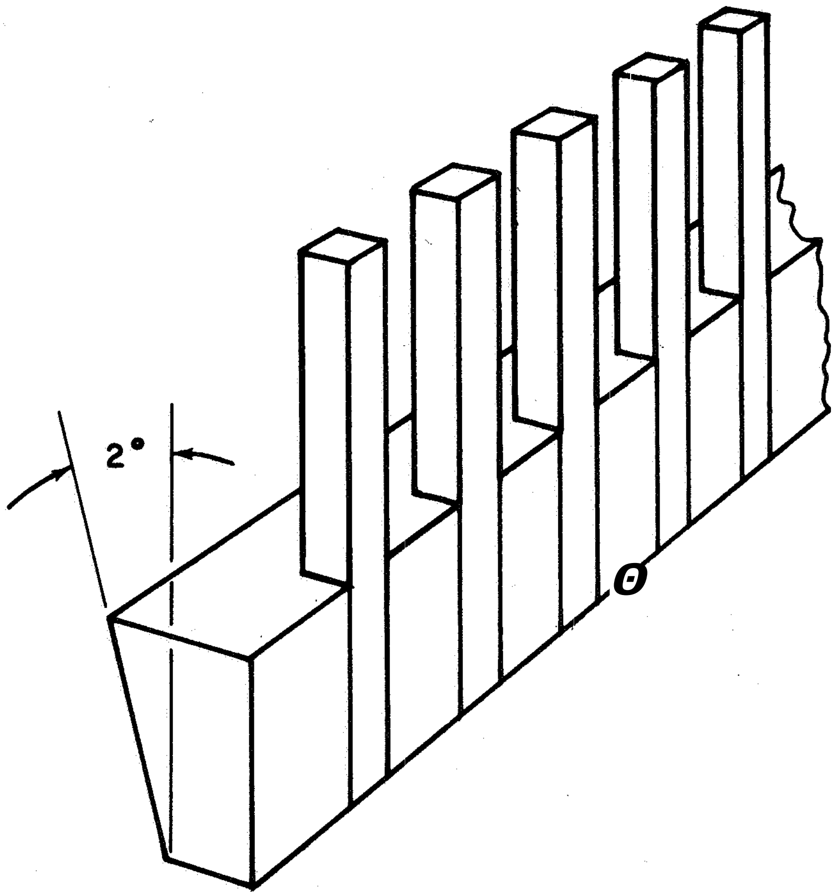


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Figure 127 SKETCH OF POTTED COMB

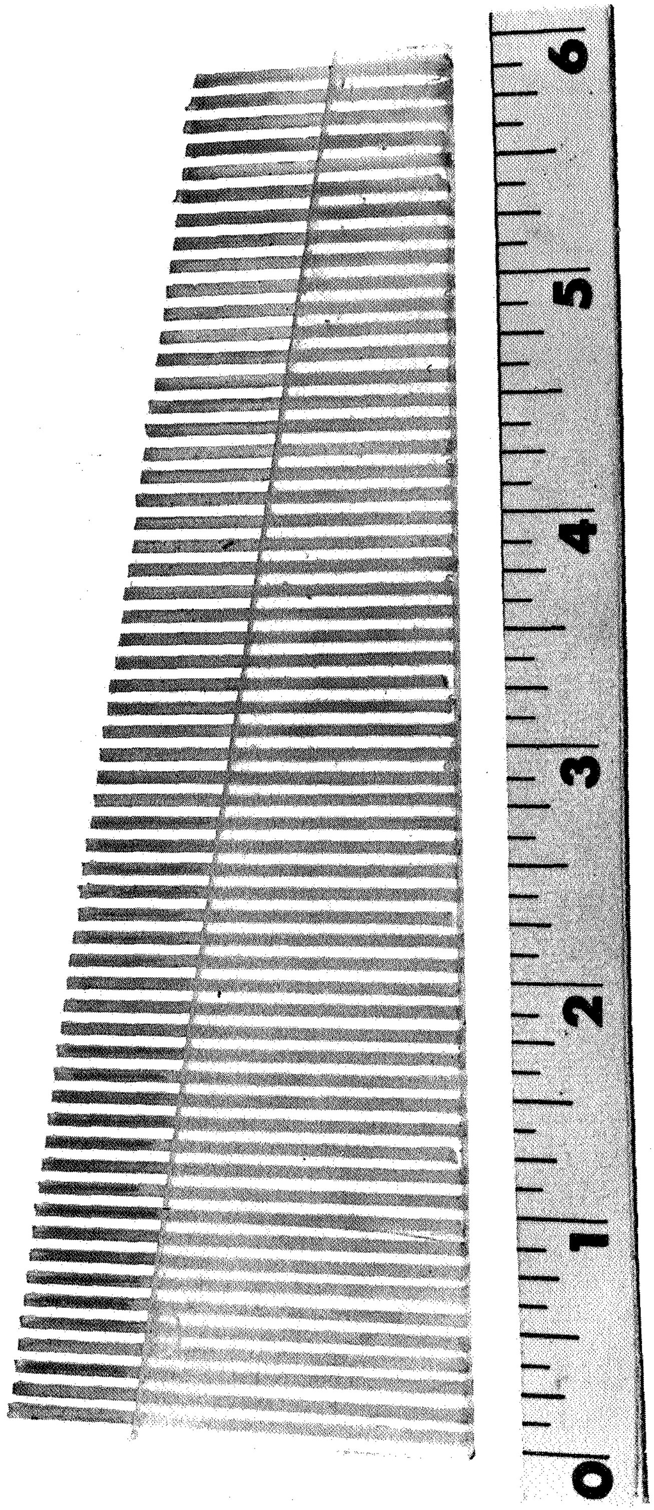

Figure 128 PHOTO OF FINISHED COMB FOR CONICAL PART

Figure 29 PHOTO OF HELICAL PATTERN ON END PLATE

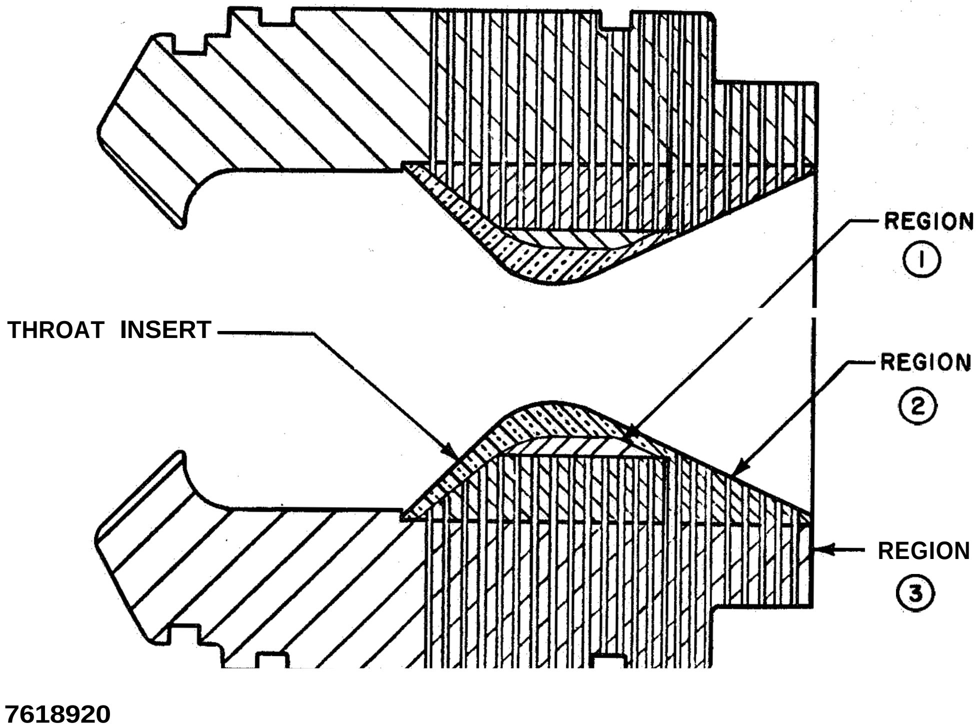

Figure 130 CROSS-SECTION DIAGRAM OF CYLINDRICAL 3-D THRUSTER

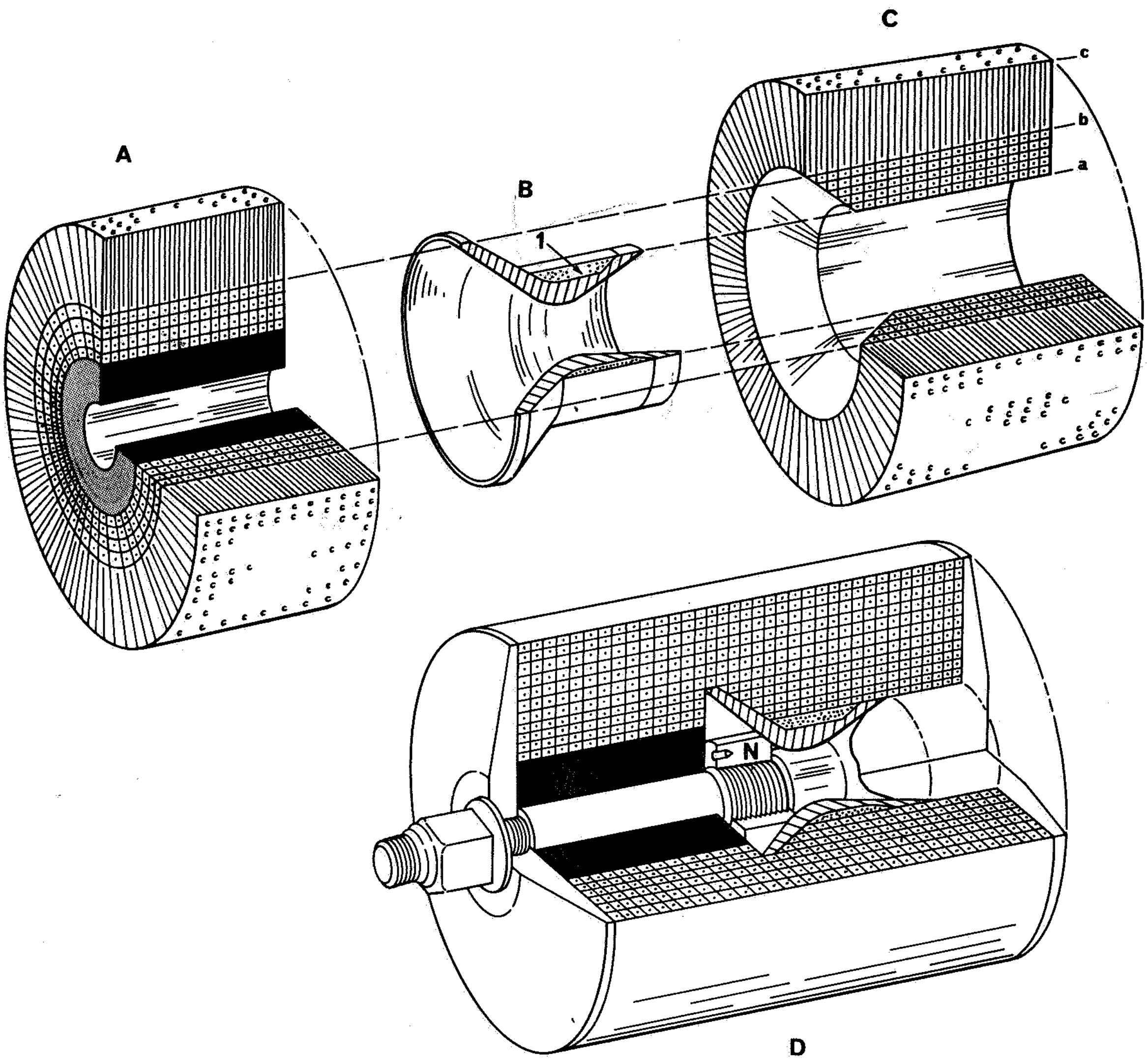

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Figure 131 DETAILS OF THREE-STEP COMB THRUSTER FABRICATION

Step 1. --The region marked (1) in section B of the figure will be filament wound and B-staged. The outer surface of the filament wound section is then machined to a cylindrical surface of the diameter at a.

Step 2. --The prepotted combs will be assembled to give a cylindrical shape as shown in A. The prepregged longitudinals and circumferentials are then added until a filled diameter equivalent to b is obtained". After B-staging this assemblage, the intkrfor is machined to fit the exterior of the filament wound throat insert so that it looks like C.

Step 3. --Resin is applied to the exterior surface of the filament wound throat insert, and B and C are joined.

Step 4. -- A second cylinder of combs as at A is assembled and joined to BC by the use of a mandrel as shown in D. The mandrel is designed so that the axes of the sections are identical. The size of the intermediate nut I is such that a core bit small enough to go through the port (1 1/4-inch diameter) for fuel and 'oxidizer will allow removal of the mandrel for final machining.

Step 5. -- The longitudinals and circumferentials will then be added to fill out the matrix of radials from b to c. These longitudinals will run the full length of the assemblage shown at D, resulting in an essentially monolithic structure.

Step 6. --The completely woven structure will be impregnated and cured, after which the mandrel and end caps will be removed.

Step 7, --Final machining to print tolerances will finish the fabrication.

2. Alternate Single Step System

The triple-deck type of construction described above is well within Avco state-of-the-art regarding cylindrical coordinate type of weaving; hence it can be relied upon for immediate fabrication of prototypes.

There is, however, a distinct possibility of weaving the entire rocket nozzle chamber in an uninterrupted process in the manner described below.

The scheme shown in Figure 132 has two banks of radial combs on each side of the metallic insert. The latter is locked on a central arbor and runs co-axial with it to a T. I. R. of ±0. 002 approximation. The arbor is also the mounting base for the radial potted combs.

A dummy porcupine P is mounted with its axis parallel to the arbor; P 'has a series of pins at the same pitch as that of the adjacent banks. The axial position of the dummy porcupine is adjusted so that its radial pins

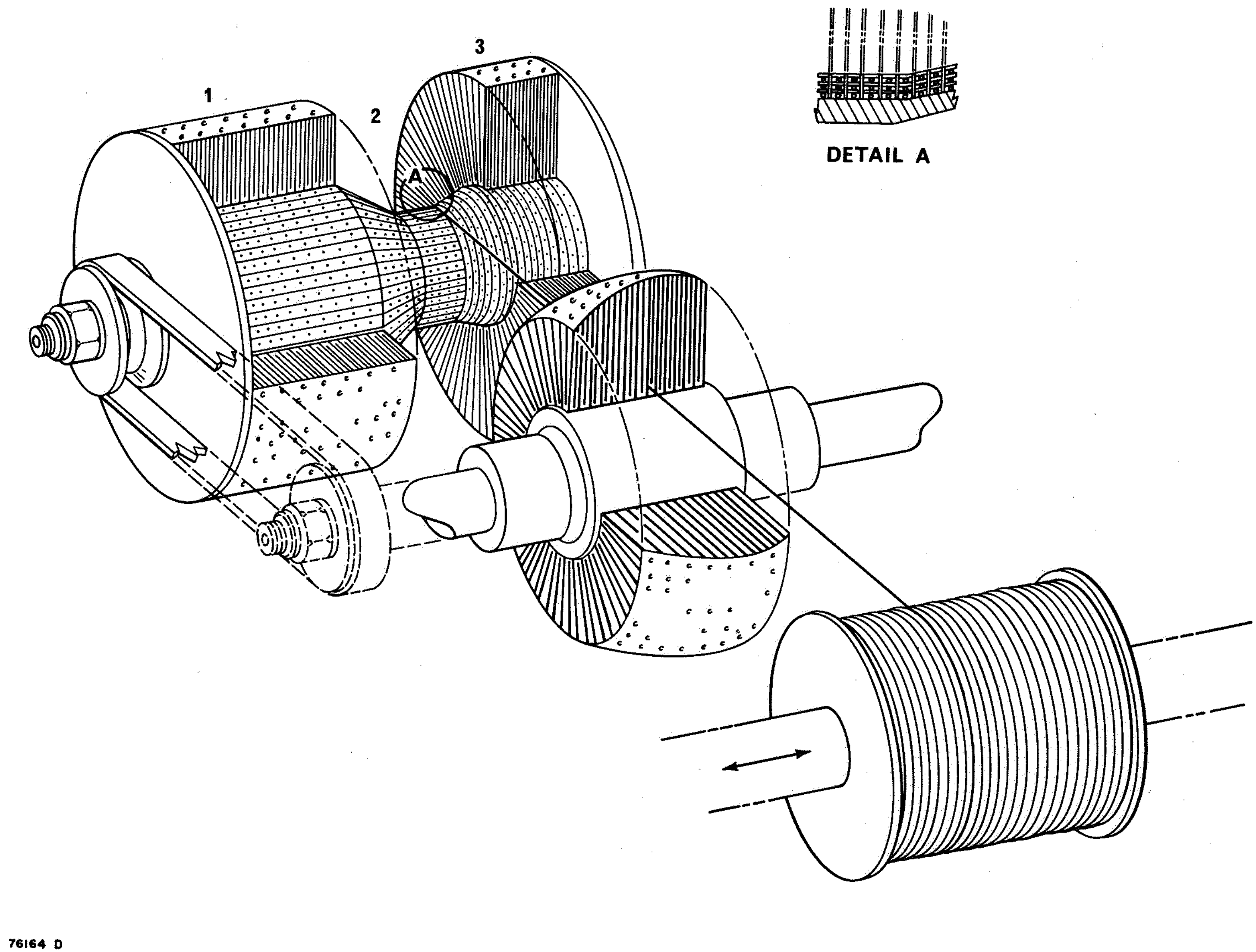

Figure 2 DETAILS OF ALTERNATE ONE-STEP COMB THRUSTER FABRICATION

form a helical extension of the quills on the adjoining banks, A filament leaving plane B, for instance, should fall right on line with the first row of pins on the dummy porcupine.

Prior to winding, the outer surface of the metallic insert is made tacky by a resin treatment. The winding starts at A, and, upon reaching B, the filament guidance is taken over by the dummy mandrel and is again relinquished to the main radial bank at C. Upon reaching D, the first circumferential layer is finished. A layer of axial elements is now deposited and tamped down by means of a flat plate such as T.

This operation is repeated a number of times (three times may be sufficient) until the square holes generated over the surface between B and C are deep enough to provide support for a bank of radial elements similar to those of the adjacent sections. When this is done, the dummy shaft can be removed and the winding can proceed directly from A to D. The depression between B and C can be eliminated either by a local gradual buildup of axial element between B and C or by continuing the winding until the diameter at the valley equals the largest desired diameter and then grinding the excess material after curing.

III. CONCLUSIONS

1) Substantial improvement has been shown in the interlaminar direction strength of several composite 'materials as compared with the reference laminates. This improvement has been shown in tensile and shear strengths and moduli despite low reinforcement content in most of the candidate materials.

2) Substantial improvement has been shown in thermal shock resistance over phenolic-glass and epoxy-glass reference laminates. These tests, however, are not use tests, and the severity may not be as high as the expected nozzle environment, although the reference laminates did show severe and extensive interlaminar cracking. Further, the tests, while both single exposure and cyclical, were not standard, so the extent of the improvement is not precisely defined. Most of the candidate composites were high in resin content, and the effect on the ablative properties requires evaluation.

3) The feasibility of producing fabric of the desired size with improved mechanical and thermal shock resistance is very good. All of the best three methods (Avco 3-D, double-loop fabric laminate, and needling) could produce correct size billets without large scale development.

4) The technology for impregnating these fabrics with phenolic resins has been developed to a high degree, although fully dense composites with pure phenolic have not been made. Composite resin impregnation, first with phenolic and then with a charring epoxy, have given composites of very low void content.

5) Chamber fabrication from Cartesian coordinate geometry fabric is a feasible method for production of at least'limited quantities, with some control over thread orientation, and essentially void free.

6) Cylindrical coordinate reinforced monolithic thrusters can be made by a comb design. The fabrics would be woven around the nozzle insert.

IV. RECOMMENDATIONS

1) Substantial improvement in thermal shock resistance and Z (interlaminar) direction mechanical properties has been shown in several new composites. It is recommended that the best candidate, in addition to the Avco method already used, be made into nozzle hardware and subjected to use tests in order to demonstrate the effect of improvement in mechanical properties. In some cases, the resin content of the composites is higher than that of the reference laminates, and the effect on nozzle performance requires evaluation. The candidate material, besides the Avco **3-D**, considered best is the double-loop fabric.

2) The second recommendation is that the double-loop technique be studied to assess properly the level of improvement possible by this method. The double-pile concept appears to be promising based on the results reported here, but the fabrication parameters have not been studied; thus substantial improvement in the already good properties can be expected from such a study. The loop density (loops/in^2), loop height, loop thread size, and normal warp and fill thread count can be varied to optimize the laminate performance.

3) The thermal shock tests performed for this study were mainly qualitative. The results, however, scanned a good range of visual change; thus quantitization appears feasible. Modifications in the direction of higher heat flux and automation of cycling to simulate chamber firing conditions may allow correlation with chamber firing results, from which a quality control test of great value could be developed.

4) The other candidate techniques are limited in potential fabric thickness and are therefore eliminated from consideration under present restrictions. Nevertheless, the possibility exists that much thicker laminae, which require fewer interlaminar regions, might, because of the stiffness of the thicker layers of reinforcement, result in less cracking. The fourth recommendation is that the effect of increased laminae thickness on the thermal shock resistance be studied so that the simpler, and less expensive, techniques might be used to gain the necessary improvement in composite properties.

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APPENDIX A

All weaving is essentially an interlacing of two sets of yarns and thus almost all looms are similar in their essential parts and corresponding mechanical action. However the fabrics they make vary over a wide range density, thickness and weave, all of which effect their strength in the various directions. Because of this wide variation in fabric geometry from relatively similar machines a short description of a woven fabric and a glossary of most used terms will follow before the description of the loom operation itself. This knowledge of fabric description and loom operation is presented so that persons without prior knowledge of weaving or loom operation will not be lost in the discussion of the difficulties encountered in the fabrication of 3-D reinforcements.

A woven fabric is a textile structure formed on a loom when two sets of yarns are interlaced at right angles to each other. See Figure A-1.

The vertical yarns are known as the warp. One yarn of the warp is called an end. The warp is a sheet of parallel yarns held in place on the loom.

The horizontal yarns are known as the filling or weft. One yarn of the filling is known as a **pick.** The filling is the yarn which is interlaced, one pick at a time, at right angles to the warp and runs from one edge of the fabric to the opposite edge in a continuous strand.

Figure A-1 illustrates a portion of a single fabric, i. e., a fabric made with one warp and one filling. Two other types of woven fabrics are:

PLY FABRICS (Figure A-2) - consist of two or more warps and two or more fillings. The two or more fabrics in a ply construction are woven simultaneously and bound together during weaving. The sketch shows a double plain weave fabric.

PILE FABRICS (Figure A-3) - are those in which an extra warp or extra filling is used to make a pile surface on one or both sides of a single ply fabric. The sketch illustrates a plush or velvet structure.

CONSTRUCTION, FABRIC COUNT, THREAD COUNT

The number of ends and picks per inch in a fabric. Expressed as 64 x 52 the first number is always the ends per inch while the second number is always the picks per inch. The sum of the ends and picks per inch in single fabrics varies from about 20 to about 500. Details of a fabric construction also include width, weight, weave and yarn specifications.

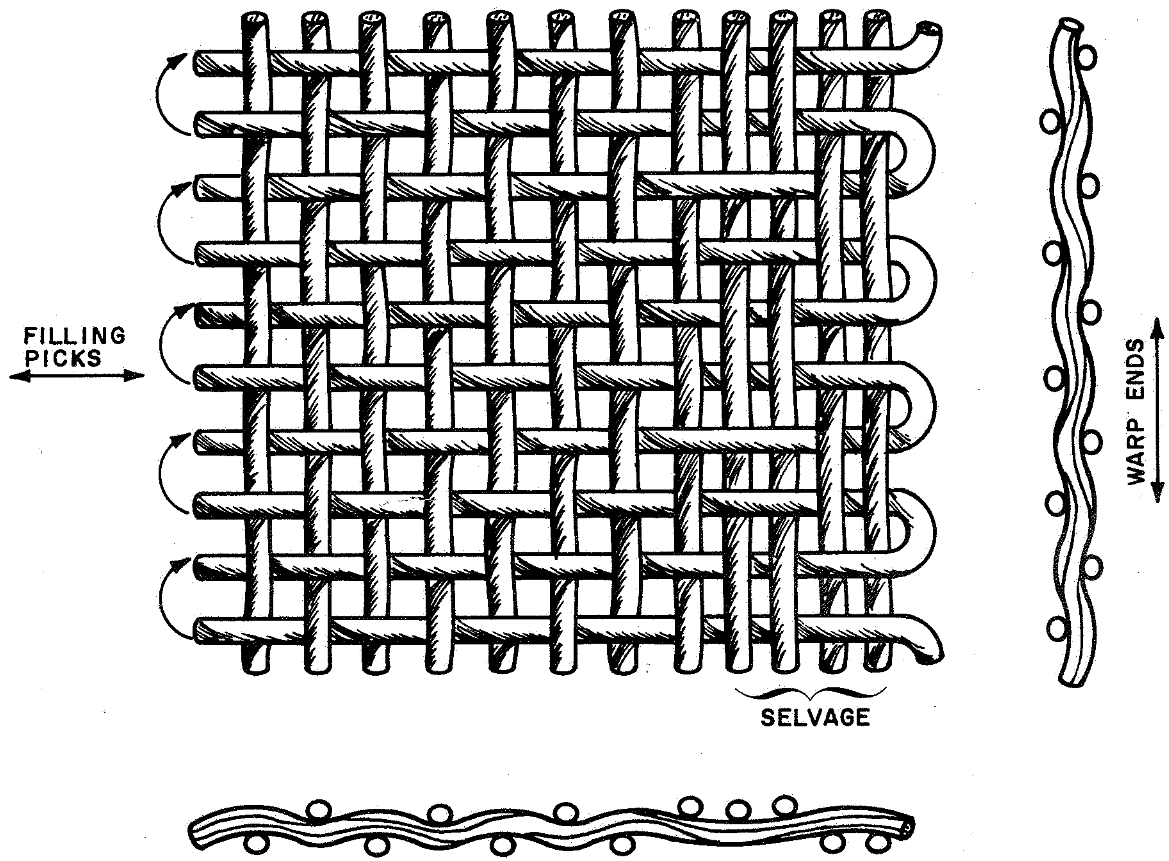

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Figure A-1 TYPICAL PLAIN-WEAVE FABRIC

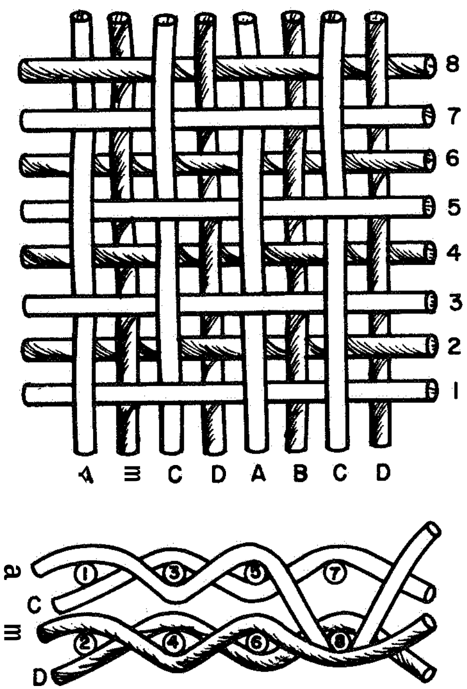

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Fig re A-2 MULTIPLE-WARP FABRIC

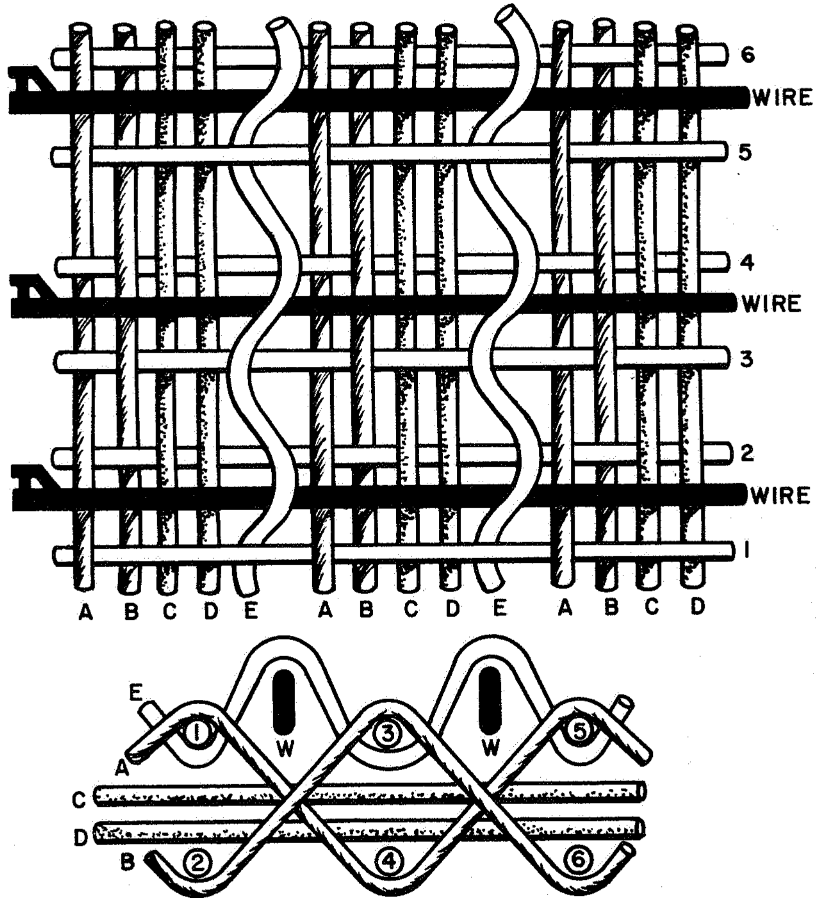


Figure A-3 TYPICAL LOOP FABRIC

DESIGN, FIGURE, INTERLACING, PATTERN, REPEAT, WEAVE

The interlacing of a specified number of ends and picks. The smallest number of ends and picks on which a particular specified interlacing takes place is known as a repeat. Usually a fabric consists of a multitude of repeats. Within a repeat each end must interlace with the picks once and each pick must interlace with the ends at least once. The smallest repeat consists of two ends and two picks.

FELLOFCLOTH

The edge of the cloth formed by the last pick or the edge nearest to the reed while the fabric is being woven.

FILLING, WEFT, WOOF

The crosswise yarns in a fabric running from selvedge to selvedge and at right angle to the warp.

FILLING EFFECT, FILLING FACE

Any fabric in which the weave allows most of the filling yarn to remain on the face of the fabric.

FLOAT

That portion of an end or pick which is not interlaced in a fabric for at least a distance of two or more picks or two or more ends.

SELVEDGE, LISTING, LIST

The lengthwise woven edges of a fabric. They are used to add strength and uniformity to the edge of a cloth in order to facilitate the weaving and finishing operations. The stronger and firmer the fabric the less need for a selvedge. The ends in a selvedge are usually of a coarser count, with more ends per inch, and a different weave than in the body of the cloth.

WARP, CHAIN, TWIST

A sheet of parallel yarns wound on a beam. The length of a warp is usually hundreds of yards.

WARP EFFECT, WARP FACE

Any fabric in which the weave allows most of the warp yarn to remain on the face of the fabric.

WEIGHTS OF FABRICS

The weight of cotton fabrics is usually given as yards per pound, based on the actual width. For cotton fabrics less than two yards per pound, the weight is usually given in ounces per lineal yard. A few special industrial cotton fabrics express weight in ounces per square yard.

Weights of filament yarn fabrics are usually given in pounds per 100 yards of fabric. Sometimes the weight is given in ounces per running yard.

Weights of woolen and worsted fabrics are given in ounces per running yard.

Single fabrics range in weight from about 1/2 to about 50 ounces per square yard.

THE LOOM

A loom is a frame or machine used to facilitate the interlacing of warp and filling yarns. Types of looms may range from a simple wooden frame to a complicated, mechanical, automatic machine. Figure A-4 is a photograph of a typical contemporary loom while Figure A-5 is a sketch of its main loom part illustrating its operation. All types of looms are alike in one respect; they hold the warp yarns in place while the filling yarns are interlaced at right angles to the warp, <u>one pick at a time</u>.

The procedure for weaving a fabric on a simple loom is as follows:

1) A plan (design) of the interlacing of the warp and filling yarns is first drawn. Figure A-1 is an example of such a plan.

2) A sheet of a specified number of warp yarns is secured to a frame of desired length and width.

3) The weaving operation takes place in the following manner:

   a) The filling yarn is interlaced through the warp in the same manner as shown in the plan. The interlacing of each pick is repeated until the entire width of the warp is traversed.

   b) After each pick is interlaced it is pressed forward to the previous pick with the fingers or with a comb-like tool.

Because each pick is interlaced across the warp by hand it is easy to understand why this method is slow and time consuming. Another disadvantage is that the fabric length is limited to the size of the frame. This method is used today only for special types of fabrics such as hand woven tapestries, Indian blankets and Oriental rugs.

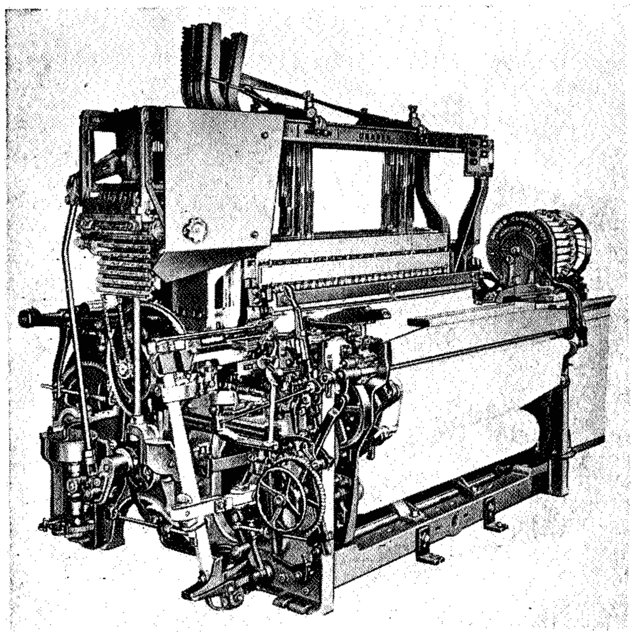


Figure A-4 TYPICAL MODERN LOOM

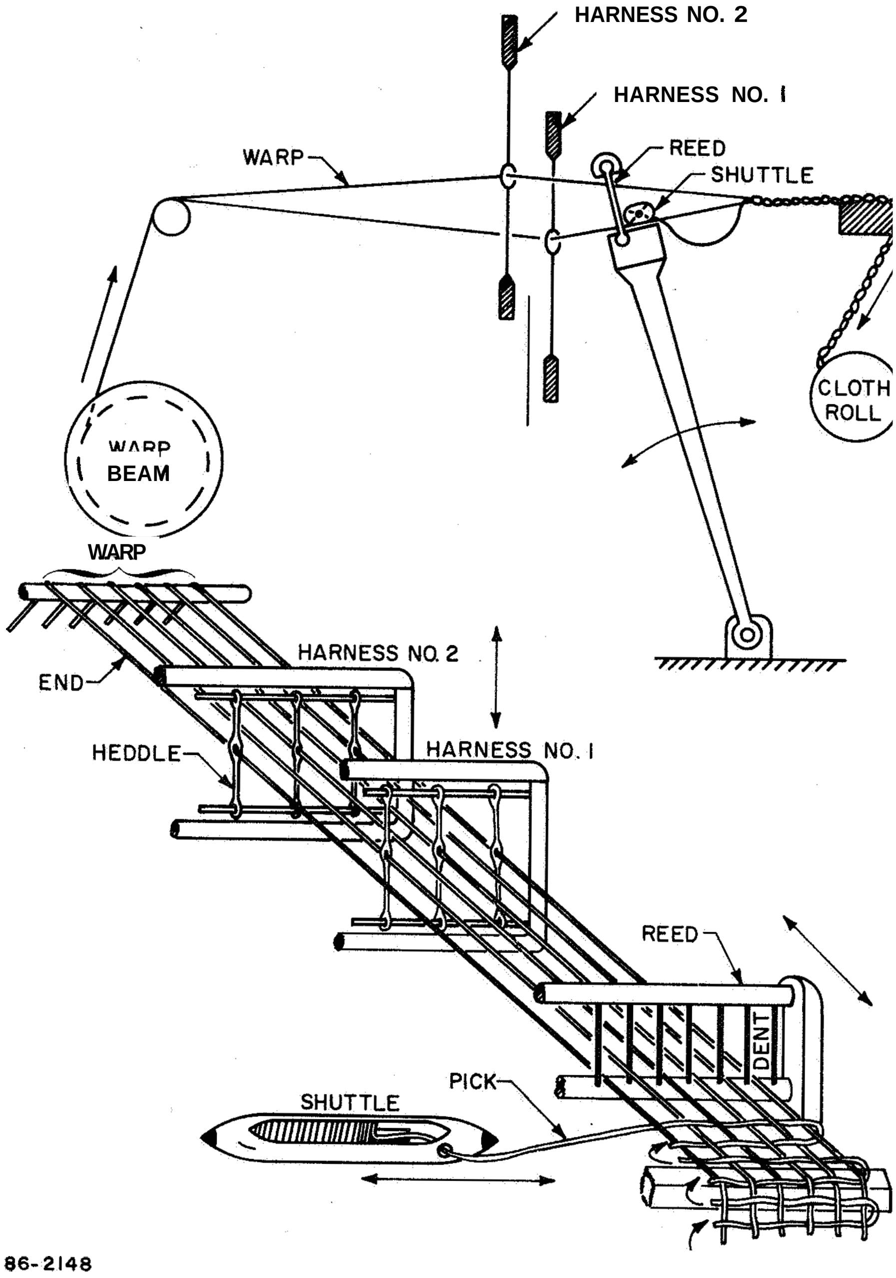


Figure A-5 SCHEMATIC DIAGRAM OF MAJOR LOOM PARTS

If, before each pick is interlaced, all the ends that are to be raised over that pick are lifted at once, a passage or opening (shed) will be formed in the warp. If the filling is in a package form which allows the yarn to unwind as the filling package passes through the shed, a great saving in time will be effected. There will be a further saving in time if a comb-like device extends across the width of the warp and is used to beat up each pick. All looms, other than simple frame types are equipped with devices to effect this saving in time. These time saving devices are known as harnesses, shuttles and reeds. A harness is used to lift the ends, the shuttle carries a suitable package of filling yarn through the shed and a reed beats up each pick to form more fabric.

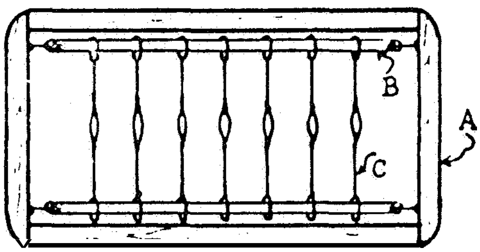
THE WEAVING PROCESS

By a series of preparatory processes consisting of winding, warping and sizing, a given number of specified yarns is arranged as a sheet of parallel ends and is wound on a large spool known as a beam. The sheet of yarn on the beam may be long enough to weave several hundred yards of cloth. Next the warp ends are drawn through the harnesses in a predetermined order. Each end is drawn through the eye of one heddle of one harness only. Then each end is drawn through the reed. The beam of warp yarn, harnesses and reed are then placed in the loom and the warp yarns are secured to the cloth roll.

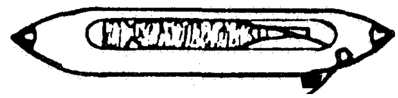
A shed is formed in the warp by raising the proper harnesses. Beforehand the filling yarn is wound on a bobbin. The bobbin is placed in a shuttle, see Figure A-6 which in turn is placed in a shuttle box. By means of a suitable mechanism the shuttle is thrown through the opening in the warp and a trailing pick of filling yarn is left in the shed. Next, the reed moves forward and presses the pick of filling into its final position in the fabric, At this time a take-up mechanism causes the warp and fabric to be pulled forward. The amount of pull forward is the same after each pick and thus a uniform number of picks per inch is placed in the fabric.

Motions		Loom Parts	Fabric
Basic	1) shedding 2) picking 3) beating-up	harnesses shuttle reed	warp filling warp & filling
Auxiliary	4) take-up	take-up mechanism	warp & fabric

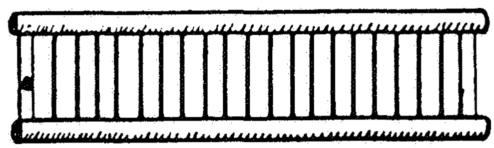
The sequence of shedding, picking, and beating-up is common to all types of looms equipped with harnesses, shuttles and reed. Speeds of looms are designated as picks per minute. A common range of loom speeds is from 120 to 240 picks per minute. A cycle of the three basic motions will therefore occur anywhere from two to four times per second.



HARNESS



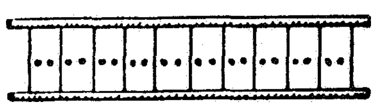
SHUTTLE



REED

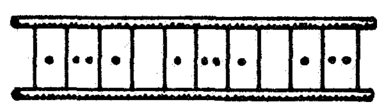
HARNESS - a frame-like device used to lift, at one time, all those ends which interlace alike with respect to the same picks. A harness consists of the frame (A), heddle bars (B), and heddles (C). The heddles can slide along the heddle bars and heddles may be added to or removed from a harness in order to accommodate all the ends of a warp. Each end of the warp is drawn through only one harness by threading the end through an eye in the center of a heddle. It takes two harnesses to weave the simplest type of fabric. Some looms are equipped with up to about thirty harnesses.

REED - a type of closed "comb" consisting of a series of equally spaced steel strips held in place by two ribs. The spaces between the steel strips are commonly called dents. The steel strips are sometimes referred to as dents and the spaces as splits. All the ends of a warp are usually drawn through the reed in a regular denting plan, i. e., 1, 2, 3, 4 or more ends are drawn through each dent. An irregular denting plan is sometimes used, that is, the number of ends drawn through each dent is not the same.



REGULAR DENTING

• = END



IRREGULAR DENTING

Reeds are numbered according to dents per inch and range in number from about 4 to about 60. The purpose of the reed is threefold; 1) to hold the warp out to a prescribed width while the ends are kept uniformly spaced, 2) to guide the shuttle in its passage through the shed, and 3) to beat up or press forward each pick to become part of the fabric.

SHUTTLE - A boat shaped device in which a bobbin of filling yarn is carried through the shed while it leaves a trailing yarn or pick.

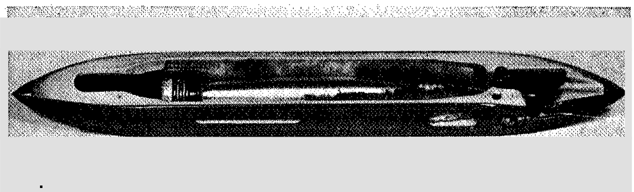
SHEDDING - the raising of prescribed harnesses so as to form an opening or "shed" between two layers of warp yarns. Regardless of the number of harnesses in the loom, any combination of any number of harnesses may be raised, provided at least one harness remains down.

PICKING - placing a pick in a shed. Most fabrics are woven with one pick per shed. Two or more picks may be inserted in a shed but they are put in one at a time, as the loom goes through its three basic motions for each pick. The number of different filling colors or different types of filling yarn that may be used in any fabric is limited by the number of shuttle boxes attached to the loom. The following is a listing of several types of looms and their limitations.

TYPES OF LOOMS

CAM	2 to 8 harnesses which are lifted by the action of cams. Harness chains are not required on these looms. Used for fabrics with simple weaves.
DOBBY	16, 20 and 25 harnesses. Requires a harness chain. Used principally for cotton and synthetic fabrics.
HEAD MOTION (C & K)	8 to 32 harnesses. 20 and 25 harnesses are most common. Requires a harness chain. Used for woolen and worsted fabrics.
JACQUARD	200 to 2600 hooks. Used for fabrics with elaborate woven designs.

BEATING-UP - when the reed moves forward and presses or beats the pick up to the fabric. The reed always moves back and forth the same distance and in the same plane. Each time a pick is put in the fabric, the warp and fabric are drawn forward automatically by the take-up mechanism. By this means a prescribed number of picks per inch are inserted in the fabric in a uniform manner.



Draper shuttle for man-made fibers, showing first pick pad tension eye.

Figure A-6 TYPICAL MODERN SHUTTLE

APPENDIX B

RESIN IMPREGNATION PROCESS METHODS

APPENDIX B

VACUUM IMPREGNATION: PRESS MOLDING METHOD

1) Mold release compression mold and seal outside mold with zinc chromate - then insert one set of mold stops at the outer edges of mold cavity and place a 9 inch x 5 inch x 3/4 inch piece of reinforcement between the stops (see Figure 65) - place cover on mold and evacuate for 20 minutes while maintaining press platen heat at 150°F.

2) Preheat resin components at 200°F and mix hot - add 1 drop of SAG antifoam agent - evacuate mixed resin and maintain at 200°F until ready for use.

3) Introduce hot resin in evacuated mold slowly in one corner of the mold until part is fully covered and maintain vacuum for 1 hour - then release vacuum and remove cover.

4) Carefully place a 9" x 6" x 1/2" aluminum separator (preheated to 150°F) over the resin - then insert a second set of molds stops and piece of reinforcement and repeat step 3.

5) Carefully place force plug over resin and slowly apply hydraulic pressure (to consolidate the impregnated reinforcement) until the predetermined distance between the top and bottom platen is obtained - regulate and maintain pressure, and cure in press for 16 hours at 235°F plus 5 hours at 300°F - cool press to 150°F and remove part.

VACUUM IMPREGNATION; PISTON PRESSURE METHOD

1) Mold release fixture completely - then position the 3" x 3" x 4 1/2" 3-D structure such that it is supported 3" from the bottom of a 4" dia. x 18" long sleeve and encapsulate lateral sides of structure only with RTV 11 silicone thus leaving the top and bottom of the structure open. Cure in fixed position overnight.

2) Preheat resin components at 200°F and mix hot - add 1 drop of SAG antifoam agent - evacuate mixed resin and maintain at 200°F until ready for use.

3) Preheat the partially assembled impregnating fixture in a 235°F oven for 1/2 hour.

4) Pour sufficient hot resin in the longest end of the sleeve such that it rests on the top face of the 3-D structure and place piston over the resin and secure fixture. Then place fixture in 235°F oven.

5) Apply vacuum at the short end of the sleeve for 10 minutes - then force resin through material with the aid of the piston by pressurizing the piston with 90 psi air pressure - as soon as resin appears at the vacuum end of the fixture, shut off vacuum and release air pressure.

6) Cure material in fixture for 16 hours at 235°F - dismantle fixture and remove part for post-curing at 300°F for 5 hours.

VACUUM IMPREGANTION: AIR PRESSURE CYCLING METHOD

1) Mold release support fixture and assemble (see Figure 63) to secure reinforcement - place the assembly in suitable container and evacuate in chamber - maintain vacuum at 150°F for 20 minutes.

2) Pre-heat resin components at 200°F and mix hot - add 1 drop of SAG antifoam agent - evacuate mixed resin and maintain at 200°F until ready for use.

3) Introduce hot resin in evacuated chamber slowly such that it is fed to the bottom of the part being impregnated - cover part with sufficient resin and maintain vacuum for 1 hour - then release vacuum and remove part.

4) Transfer part to pressure pot and apply 5-90 psi air pressure cycles in 15 minute intervals - remove part and cure and post cure accordingly.

APPENDIX C

TEST DATA

DATA FOR EPOXY RESIN SYSTEM (USED IN AVCO/SSD 3-D)

Tensile Properties

Sample	Area (inches^2)	E x 10^{-6} psi	Tensile Strength psi	% Total Strain
1	0.058	0.370	7660	4.13
2	0.058	0.370	7810	3.31
3	0.057	0.380	7410	3.68
4	0.058	0.370	7750	4.80
5	0.057	0.380	7700	4.92
6	0.058	0.37	7980	4.06
7	0.057	0.36	8020	4.50
Average	0.058	0.37	7760	4.20

Compressive Properties

1	0.380	25400
2	0.390	19600
3	0.40	28400
Average	0.390	24500

Shear Properties

1	0.140	5870
2	0.130	6090
3	0.130	5870
Average	0.133	5940

AVCO/SSD 3-D REINFORCED EPOXY RESIN

Tensile Properties

Avco Code Number Sample	Orientation	Modulus psi x 10^{-6}	Strength psi
909-41	Z	2.12	39,500
	Z	2.22	37, 500
	X	2. 31	33,500
	X	1. 64	29,500
	X	1.87	27, 300
909-107	Z	2. 29	35,500
	X	2. 51	38,600
	X	2.08	
	X	2. 30	26,900
	X	2. 13	26,000

Torsion Test

909-41	Z	0.410	12,200
909-107	Z	0.44	11, 300
	Z	0.43	13,000

PROPERTIES OF PHENOLIC AND PHENOLIC-EPOXY IMPREGNATED RAD 3-D REINFORCEMENT

Avco/RAD Code No.	909-1 (48-1)	909-1 (48-2)	874-5 (26)
Material Composition	Fiberglass/ Phenolic	Fiberglass/Phenolic-Epoxy	Fiberglass/Epoxy
Physical Properties*			
Woven Density, gm/cm^3	1.37	1.38	1.36
Impregnated Density, gm/cm^3	1.77	1.90	1.80
Porosity, percent by volume	11.6	1.6	----
Resin Content, percent	22.6	26.9**	28.0
Mechanical Properties*(Vertical Yarns-Z axis)**			
Prop. Limit, psi	4050	4950	2200
Yield Stress, psi	17050	23400	----
Ult. Tensile Stress, psi	33000	41700	38200
Elastic Modulus, psi $\times 10^{-6}$	2.50	2.65	2.68
Total Strain, percent	2.13	2.38	3.18

*Values reported are average of three measurements
**Total resin content - 20.0 percent phenolic + 6.9 percent Epoxy
***Values reported are average of two sets

RAYPAN 3-D EPOXY SYSTEM

TENSION TESTS AT 75°F, 0.005 "/"/MIN.

PARALLEL TO LAMINATES

Spec. No.	1	2	3	4	5	6	7	8	9	>0
Area, inches	0 039	0 039	0. 039	0 039	0 039	0 039	0. 039	0. 039	0 039	0 039
Prop. Limit, psi	1400	3600	4[illegible]00	Z750	Z750	3000	4000	4[illegible]00	1750	4250
Ultimate Tensile Strength, psi	6600	14 000	19, [illegible]00	17 300	Z[illegible]. 700	Z3 600	1 500	Z0 >00	9350	19, 000
Modulus, psi x 10-6	2. 55	2. 91	3 65	3 35	3 5Z	3. 52	3 54	3 35	3 Z4	3 07
Percent Total Strain	0 48	0 68	0 78	0 74	1 5Z	1. 40	0 66	0 8Z	0 52	1 29

RAYPAN 3-D EPOXY SYSTEM

Torsion Tests 75°F

About Axis Perpendicular to "Laminations"

Spec. No.	1	2	3	4
Diameter, inches	0. 314	0. 310	0. 313	0. 310
Gage Length, inches	1.0	1.0	1.0	1.0
Modulus, psi x 10^{-6}	471,000 psi	533,000	533,000	471,000
Ultimate Shear Strength, psi	6700 psi	6320	5880	5910
Total Twist in Degrees	12°	10°	9°	10°

Resin Content

Specimen No.	Percent Resin
1	23. 0
2	30. 5
3	24.75
4	24. 6
5	27.4
6	24. 1
7	25. 6
8	26. 0
9	24. 7
10	28. 3

AVCO/SSD 3-D "S" GLASS EPOXY SYSTEM (BLOCK NO. 19)

Tension Tests	75°F,	0. 005 "/"/min
Vertical Direction (Z axis)		
Spec. No.	1	2
Area, inches2	143	143
Prop. Limit, psi	2600 psi	1800
Ultimate Tensile Strength, psi	36,000	40,800
Modulus, psi x 10^{-6}	2. 67	2. 69
Total Strain, percent	3. 6	2.77

AVCO/SSD 3-D "S" GLASS EPOXY SYSTEM (BLOCK NO. 19)

45 Degree Angle in X-Y Plane		
Spec. No.	1	2
Area, inches2	0. 141	0. 141
Prop Limit, psi	1900	1650
Ultimate Tensile Strength, psi	12,800	12,700
Modulus, psi x 10-6	1.56	1.49
Total Strain, percent		6. 75

1

AVCO/SSD 3-D "S" GLASS EPOXY SYSTEM (BLOCK NO. 19)

Compression Tests	75°F	.005"/"/min.	
Vertical Direction (Z axis)			
Spec. No.	1	2	3
Area, inches^2	0.109	0.110	0.110
Prop, Limit, psi	11,200	13,600	14,200
Ultimate Compressive Strength, psi	52,800	59,600	59,100
Modulus, psi x 10^{-6}	1.93	2.0	2.20
Total Strain, Percent	6,54	5.93	6.34

AVCO/SSD 3-D "S" GLASS EPOXY SYSTEM (BLOCK NO. 19)

Torsion Tests	75°F	
Twist About Vertical Direction (Z axis)		
Spec. No.	1	2
Diameter, inches	0.377	0,377
Gage Length, inches	1.0	1.0
Shear Modulus, psi	500,000	571,000
Ultimate Shear Strength, psi	10,100	14,500
Total Twist in Degrees	130	130

AVCO/SSD 3-D "S" GLASS EPOXY RESIN (BLOCK NO. 19)

Twist About 45 Degrees Direction in X, Y Plane

Spec. No.	1	2
Diameter, inches	0.379	0.379
Gage Length, inches	1.0	1.0
Shear Modulus, psi	800,000	615,000
Ultimate Shear Strength, psi	10,700	10,000
Total Twist in Degrees	190°	185°

Resin Content: One sample for 3/8" dia. x 1/2 in. long - 22.5 percent*

*This value may be low

CIBA 6005 RESIN

Sample	Area inches2	Tensile Properties Modulus psi x 10^{-6}	Strength psi	Percent Strain	Proportional Limit psi
1	0. 113	0. 38	6360	2. 15	1060
2	0.112	0. 37	3160*	0. 90	1300
3	0. 115	0. 380	3880*	1. 80	980
4	0. 113	0. 370	3150*	0. 90	1100
Average	0. 114	0.375	4140	1. 26	1110

Torsion Properties (Torsion on Circular Bars)

		0. 130	4840		

Butt Tensile

			1670		

*Fracture Initiated by small fabric inclusions

FIBERGLASS LAMINATE CIBA 6005 RESIN 28.2 PERCENT 413 PLY DENSITY 1.90

Tensile Properties

Parallel (In Plane of Laminates)

Sample	Area inches^2	Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	Percent Total Strain
1	0. 141	3.33	44,000	9000	1. 62
2	0. 141	3. 27	43,300	8600	1. 60

Perpendicular (In Plane of Laminates)

1	0. 141	3.82	43, 600	6600	1.47
2	0. 141	3.92	55,000	8000	1.79
3	0. 141	3. 82	44,000	6400	1.44

Perpendicular to Laminates

1	0.141	1.07	2,050	850	0. 30
2	0. 141	1.11	3,060	1000	0. 36

Torsion Tests

0. 380	3, 630
0. 280	2,710

NEEDLED MATT AND FABRIC (CIBA 6005) SIMMONS "S" GLASS 60.3% RESIN 909-56 (1.46 DENSITY)

Tensile Properties

Parallel

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.124	1.54	17,500	2500	1.56
2	0.130	1.36	15, 700	2800	1.50
3	0.131	1.53	19,000	2700	1.55
4	0.131	1.67	20,000	2200	1.54
Average					

Perpendicular

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.129	1.45	18, 100	2900	1.60
2	0.129	1.59	18,500	2900	1.48
Average					

Butt Tensile

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi
1			3200
2			3870
Average			

Torsion Tests

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi
1		0.240	6220
2		0.25	6570
Average			

Notched Tensile Bar Shear Tests

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi
1			6019
2			5390
Average			

J.P. STEVENS NEEDLED FABRIC "S" GLASS
CIBA 6005 (70.2%) 909-68

Tensile Properties
Parallel (Warp)

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.130	1.44	12,100	2700	1.08
2	0. 130	1.33	13, 100	2900	1. 13

Perpendicular (Fill)

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0. 130	1.21	12,400	2700	1.20
2	0.130	1.21	11,400	2800	1.10

Butt Tensile

			3430		

Torsion Tests

		0.190	5920		

10 PLY TUFTED (CIBA 6005 70.2% RESIN) 909-75
J.P. STEVENS "S" GLASS

Tepsile Properties
Parallel

Sample	Area Inches^2	**Modulus** psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.047	1.25	8380	2300	1.46
2	0.047	1.49	9090	2500	1.03
Average					

Perpendicular

1	0.048	1.37	13, 100	2650	1.4
2	0.047	1.39	14, 500	2450	1.44

Butt Tensile

			1770		

Torsion

		0.180	4840		

J.P. STEVENS NEEDLED "S" GLASS FABRIC
(19.6% RESIN) DENSITY 2.0
909-85

Tensile Properties
Parallel

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.078		13,600	3200	
2	0.079	3.55	21,000	4600	1.04
Average					

Perpendicular

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.079	3.82	21,000	7800	0.76
2	0.080	3.95	21,000	7200	0.67

Butt Tensile

848

Torsion Test

0.27 3060

4

J.P. STEVENS "S" GLASS NO.3
NEEDLED FABRIC COMPRESSED TO HIGH DENSITY
(31.5% RESIN CIBA 6005) 909-103 (DENSITY 1.75)

Tensile Properties
Parallel (Warp Direction)

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.112	2.62	22,000	6800	1.14
2	0.113	2.67	20,700	7200	1.14
Average					

Perpendicular (Fill Direction)

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.114	2.89	23,200	6800	1.04
2	0.114	2.86	27,500	11,000	1.16
Average					

Butt Tensile

3610

Notched Tension Bar Shear

5140

NEEDLED FABRIC J.P. STEVENS "S" GLASS
CIBA 6005 (69.9% RESIN) 909-59 (DENSITY 1.37)

Tensile Properties
Parallel

Sample	Area Inches^2	Modulus .psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.130	1.23	11,600	3800	1.04
2	0.130	1.34	11, 700	3300	0.99
Average					

Perpendicular

1	0.130	1.37	12,500	5000	1.10
2	0.130	1.36	12, 900	3700	1. 13

Butt Tensile

3240

Torsion Test

0.21 6010

Notched Tensile Bar Shear Test

3970

VALRAY CO. BRAID (NO LOCK)
909-105, 909-106

Axial Tensile Properties

Sample	Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
105	1.22	3580	1200	0.34
106	1. 16	2690	1700	0.28

SIMMONS STAPLE "S" GLASS NEEDLED MATT FABRIC
CIBA 6005 RESIN 909-114

Tensile Properties
Parallel

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.080	0.88	8030	1700	1.08
2	0.079	0.72	5900	1500	.92
		Perpendicular			
1	0.080	0.94	9660	2600	1.24
2	0.081	1.03	8890	2000	1.12
		Butt Tensile			
			3310		
		Torsion			
		0.170	5400		

J.P. STEVENS "S" GLASS NEEDLED FABRIC MATT
CIBA 6005 RESIN VACUUM IMPREGNATED 909-145

Tensile Properties

Parallel

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.117	2.01	15,600	2500	0.95
2	0.117	1.98	17,300	2000	1.09

Perpendicular

1	0.117	1.77	14,000	2100	1.07
2	0.117	1.58	12,800	2500	1.08

Butt Tensile

		2690

Torsion Test

0.230	4940

J.P. STEVENS "S" GLASS NEEDLED MATT FABRIC VACUUM IMPREGNATED CIBA 6005 RESIN 909-146

Tensile Properties

Parallel

Sample		Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.116	2.25	20300	6300	1.13
2	0.115	2.00	16100	7500	0.90

Perpendicular

Sample		Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.118	1.83	15800	7000	1.09
2	0.118	1. 78	17, 100	6200	1.30

Butt Tensile

3950

Torsion

0.270 4940

J.P. STEVENS NEEDLED "S" GLASS FABRIC
PRESSURE MOLDED
27.5% CIBA 6005 RESIN 909-147 (1.85 DENSITY)

Tensile Properties
Parallel

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.112	3.52	32,700	9100	1.14
2	0,112	3.47	34, 000	7500	1.28

Perpeedicular

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.114	2.89	25,300	6500	1.22
2	0.114	3. 13	25,300	6500	1. 19

Butt Tensile

3080

Torsion

0.370 5610

J.P. STEVENS "S" GLASS NEEDLED MATT
28.8% CIBA 6005 RESIN PRESSURE MOLDED (1.84 DENSITY)
90 9-148

Tensile Properties
Parallel

Sample	Area Inches^2	Modulus psi x 10^{-6}	Strength psi	Proportional Limit psi	% Total Strain
1	0.112	3.50	32, 900	8800	1.20
2	0.112	3.42	31, 500	8900	1.20
		Perpendicular			
1	0.112	2.99	24,600	6900	1.22
2	0.113	2.91	25, 800	6700	1.28

Butt Tensile

2690

Torsion Tests

0.360 5650

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